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CELDAS METALICAS ENCAPSULADAS EN GAS SF6, PARA SISTEMAS EN 60kV

INFORME DE SUFICIENCIA

PARA OPTAR EL TÍTULO PROFESIONAL DE:

INGENIERO ELECTRICISTA

PRESENTADO POR:

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CELDAS METALICAS

ENCAPSULADAS EN GAS SF6,

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A mis compañeros y amigos de ELECTROWERKE S.A., por su generosidad y permanente buena disposición para acompañarme en el trabajo.

SUMARIO

El presente informe comprende la presentación y descripción de las celdas metálicas encapsuladas en gas SF6, denominadas C-GIS, para uso en alta tensión 60kV. En el Perú conocemos un diseño similar de celdas, pero solo aplicado en media tensión hasta 36kV.

En la actualidad, la técnica de las celdas C-GIS, cobra enorme vigencia, no solamente por sus importantes aportes en el aspecto técnico y económico, sino también por razones medio ambientales.

De manera complementaria, el presente informe incluye un capítulo específico correspondiente a la confiabilidad de las subestaciones eléctricas, y un acápite dedicado al análisis comparativo entre las tecnologías correspondientes a la extinción del arco en vacío y en SF6.

El objeto de este trabajo es presentar las celdas metálicas blindadas C-GIS, como una solución técnicamente adecuada y económicamente conveniente, para que sea considerada en los futuros proyectos de transmisión en 60kV a nivel nacional.

Cabe señalar que, aun cuando el presente trabajo hace mención a los interruptores en vacío para tensiones de hasta 145kV, el trabajo está centrado en el nivel de 60kV, y de modo específico en las celdas metálicas blindadas C-GIS en 60kV.

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PROLOGO

El presente trabajo tiene como finalidad dar a conocer una solución técnica innovadora para ser utilizada en subestaciones de alta tensión, específicamente en los sistemas en 60kV, mediante el empleo de celdas blindadas en gas SF6, denominadas C-GIS, cuyas características y aportes técnicos se detallan más adelante.

La característica fundamental de las celdas C-GIS en 60kV, materia del presente trabajo, es el empleo de interruptores al vacío en alta tensión, además de la aplicación de gas SF6 con baja presión, como medio dieléctrico eficiente para reducir las distancias eléctricas de las partes vivas dentro de la celda y reducir las dimensiones del conjunto.

Cabe señalar, que la tecnología aquí mencionada es ampliamente difundida desde hace varios años en países como Japón y Corea, así como en otros países industrializados del Asia. Dicha tecnología, sin embargo, es poco conocida en nuestro medio y aún no está disponible para su comercialización en nuestro mercado.

Hasta el momento, todos hemos aprendido que el modo habitual de construir subestaciones, con aislamiento en aire, para 60kV, es la solución óptima, que cumple con los requerimientos de nuestro sistema. Sin embargo, la creciente importancia de nuevos factores determinantes en el costo de una subestación, y que antes no eran contemplados, plantean hoy la necesidad de una evaluación económica más completa y rigurosa, antes de decidir que tipo de subestación debemos construir.

No hay duda de que para las nuevas instalaciones, antes de tomar una decisión acerca de que solución emplear, se deberá tomar en cuenta, más allá de la inversión en la compra de equipos, una serie de aspectos, tales como el costo del terreno, el costo del mantenimiento calculado a lo largo de la vida útil de la instalación, el costo de la obra civil, el tiempo que tomará la ejecución de la obra, la confiabilidad del sistema, etc.

A modo de ejemplo, en el último capítulo, se plantea una comparación entre los dos tipos de instalaciones, una empleando interruptores en SF6 y equipo convencional y otra empleando celdas C-GIS con interruptores de vacío. Los resultados que se muestran confirman que, dependiendo de la aplicación, las celdas blindadas C-GIS pueden ser una a considerar en futuros proyectos.

Debido a que el carácter del presente trabajo es fundamentalmente de divulgación, no se incide en aspectos técnicos tales como el diseño de la cámara de interrupción, ni en los múltiples problemas físicos que los fabricantes han debido superar, para lograr finalmente una solución técnica de vacío en alta tensión. Al respecto se sabe que se ha empleado ingeniería de avanzada en la modelación del arco eléctrico, mecanismos especiales para la difusión y distribución del arco, mejora en los materiales de contacto, etc., todo ello sin perder de vista el aspecto económico final.

Preservando el sentido de divulgación de este trabajo, al final se incluyen además de algunos catálogos, algunas publicaciones técnicas, en Inglés, de investigaciones relativas al diseño de la cámara de interrupción en vacío, así como relativas a los interruptores en SF6 y su implicancia con el medio ambiente.

CAPITULO I
ANTECEDENTES Y DESARROLLO TECNICO

1.1 Introducción

En el Perú los niveles de tensión más utilizados en transmisión, son 220kV, 138kV y 60kV, siendo las subestaciones mayormente del tipo convencional, es decir con aislamiento en aire y montaje al exterior. Unas muy pocas instalaciones son del tipo encapsuladas GIS, en 220kV.

Las celdas C-GIS en 60kV están orientadas a sustituir de manera eficaz los equipos de 60kV con aislamiento en aire, cuando se tiene limitaciones de terreno o espacio, cuando existe un alto grado de contaminación, o cuando se prevé condiciones sísmicas severas.

1.2 Instalaciones en 60kV

En 60kV, la solución más conocida y ampliamente usada es la subestación convencional. En ella se emplea equipos más sencillos y de menor costo inicial que el de otras soluciones.

Las instalaciones convencionales son construidas para trabajar a la intemperie, sin embargo también existen instalaciones al interior, cuyo equipamiento se caracteriza por ser compacto y con línea de fuga mínima, debido a que la instalación está concebida para funcionar bajo techo, protegida del medio ambiente. Este tipo de subestación se construye normalmente dentro de un edificio, especialmente diseñado para tal fin. Esta solución tiene un costo considerablemente mayor que el de una subestación convencional. A nivel nacional, la mayoría de estas instalaciones se concentra en la ciudad de Lima.

Desde el punto de vista del mantenimiento, las instalaciones expuestas a la intemperie son las que demandan mayor frecuencia de servicio (limpieza, pintura, tratamiento, etc.).

La solución mediante celdas metálicas C-GIS en 60kV, constituye un nuevo concepto en subestaciones. Es una variante de la solución GIS. Tiene las propiedades de ahorrar espacio, alta confiabilidad y bajo mantenimiento, entre otras, con la ventaja adicional de no emplear gas SF6 para extinguir el arco, porque emplea interruptores de vacío, y que el medio aislante es gas con baja presión. (Ver Tabla N° 1.1).

Tabla N° 1.1 Comparación de Áreas de terreno para Instalaciones en 72.5 kV.

Nivel de Tensión (kV)	72.5kV
Instalación convencional con aislamiento en aire AIS	100%
Instalación de celdas C-GIS	22%

Las celdas C-GIS son un sustituto de los equipos con aislamiento en aire, y se pueden instalar a la intemperie o también en el interior de un edificio. (Ver figura 1.1)

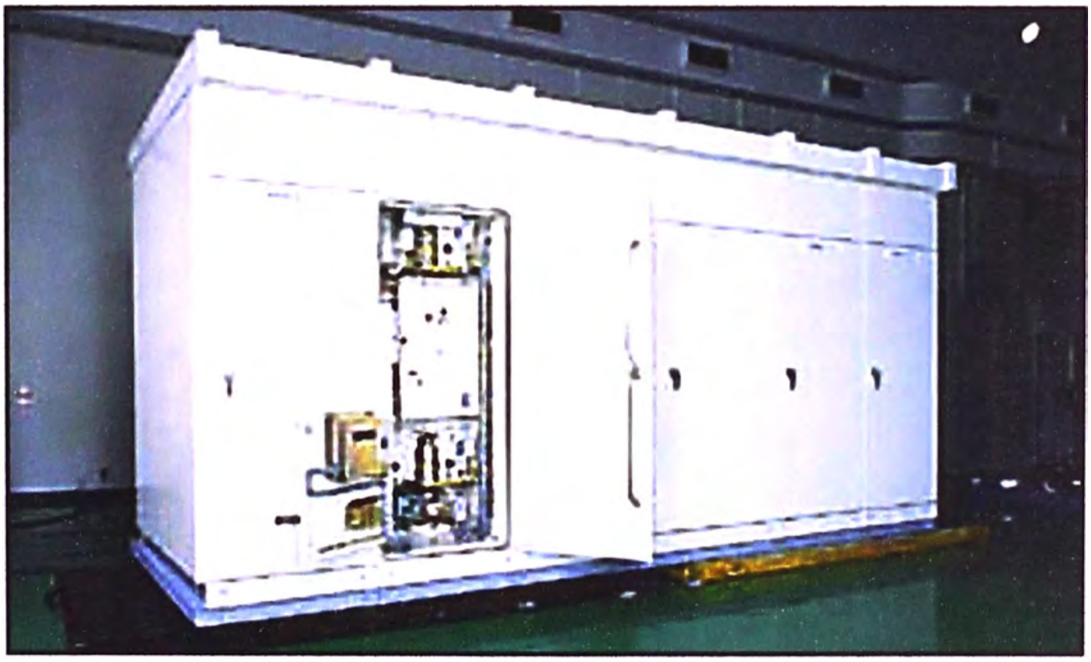


Figura 1.1 Celdas C-GIS previstas para ser montadas al interior, en 72,5kV

1.3 Aportes de tecnología

Desde los años 80, la tecnología de media tensión dio un vuelco importante en el campo de los interruptores, con el desarrollo y posterior perfeccionamiento del interruptor con botellas en vacío. Al comienzo hubo muchas dificultades, específicamente en la cámara de extinción o ampolla de vacío, las cuales fueron gradualmente superadas, y dieron lugar a que el interruptor de vacío se convirtiera en el interruptor por excelencia para la media tensión. (Ver Figura 1.2)

La tecnología de interrupción en vacío, una vez descubierta, fue desplazando otras tecnologías como la del pequeño volumen de aceite y la del SF6, cubriendo paulatinamente todos los niveles de la media tensión para luego incursionar en alta tensión. Así, puede decirse que gracias al aporte de esta tecnología, originalmente desarrollada para media tensión, hoy se dispone también de interruptores al vacío en 60kV y hasta en 170kV. (Ver Figura 1.3)

Por otro lado, el empleo del gas SF6 a presión, como medio aislante en sistemas de alta tensión, se conoce desde hace varias décadas, específicamente en los sistemas encapsulados tipo GIS. Esta técnica conlleva el empleo de altas presiones de gas, con el objeto de aumentar la rigidez dieléctrica del medio e indirectamente reducir de manera sustancial las distancias eléctricas y, consecuentemente, disminuir el tamaño de la instalación. (Ver Figura 1.4)

El empleo del gas SF6 a baja presión, como agente aislante, es una aplicación muy difundida en equipos de media tensión. Ejemplos de su utilización lo tenemos en el caso de seccionadores de apertura bajo carga, en interruptores de recierre o reclosers, en interruptores de media tensión para instalación al exterior y en celdas de media tensión presurizadas. Esta misma técnica, usada exitosamente en la media tensión, fue también adoptada desde hace algunos años, para aplicaciones en alta tensión. Este aporte tecnológico para soluciones en alta tensión, lo podemos apreciar hoy en los interruptores en vacío de alta tensión para instalación al exterior y en las celdas metálicas de 60kV. (Ver Figura 1.5)

La suma de la técnica del interruptor de vacío en alta tensión y del empleo de gas SF6 como medio aislante a baja presión, constituyen el mayor aporte tecnológico utilizado en la concepción de las celdas metálicas C-GIS en 60kV. (Ver Figura 1.6)

VCB de tanque vivo
Rangos de fabricación
Tensión : 36kV hasta 170kV
Corriente : 1250 a 2000A
Capacidad de interrupción : 25kA / 31.5kA
Características
Alta confiabilidad
Reducido costo de mantenimiento
Interruptor de rendimiento superior

145kV

VCB de tanque muerto con pequeño volumen de gas
Rangos de fabricación
Tensión : 36kV hasta 72.5kV
Corriente : 800 a 2000A
Capacidad de interrupción : 25kA / 31.5kA
Características
Excelente rendimiento
Gas SF6 a baja presión como aislante
Reducido costo de mantenimiento
Comportamiento anti-sísmico
Fácil instalación

72.5kV

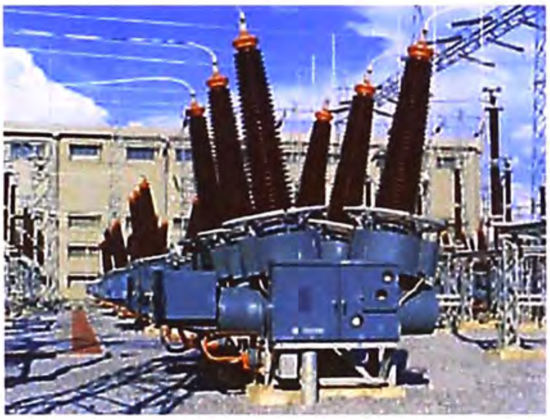
Interruptor de tanque muerto con aislamiento en aire seco Tipo VCB

Rangos de fabricación
Tensión : 72.5kV
Corriente : 1250 a 2000A
Capacidad de interrupción : hasta 31.5kA
Características
No empleo de gas SF6
No licuefacción del gas con temperatura ambiente (punto de licuefacción -180°C)
Larga vida útil y mantenimiento más sencillo que a un interruptor con gas.

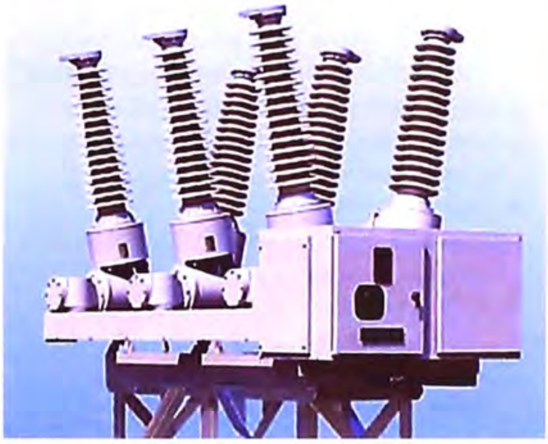
Figura 1.2 Interruptores de vacío VCB (Tipo exterior)

550kV

300kV



245kV



72.5kV

Figura 1.3 Interruptores en SF6 con aislamiento en aire (AIS)

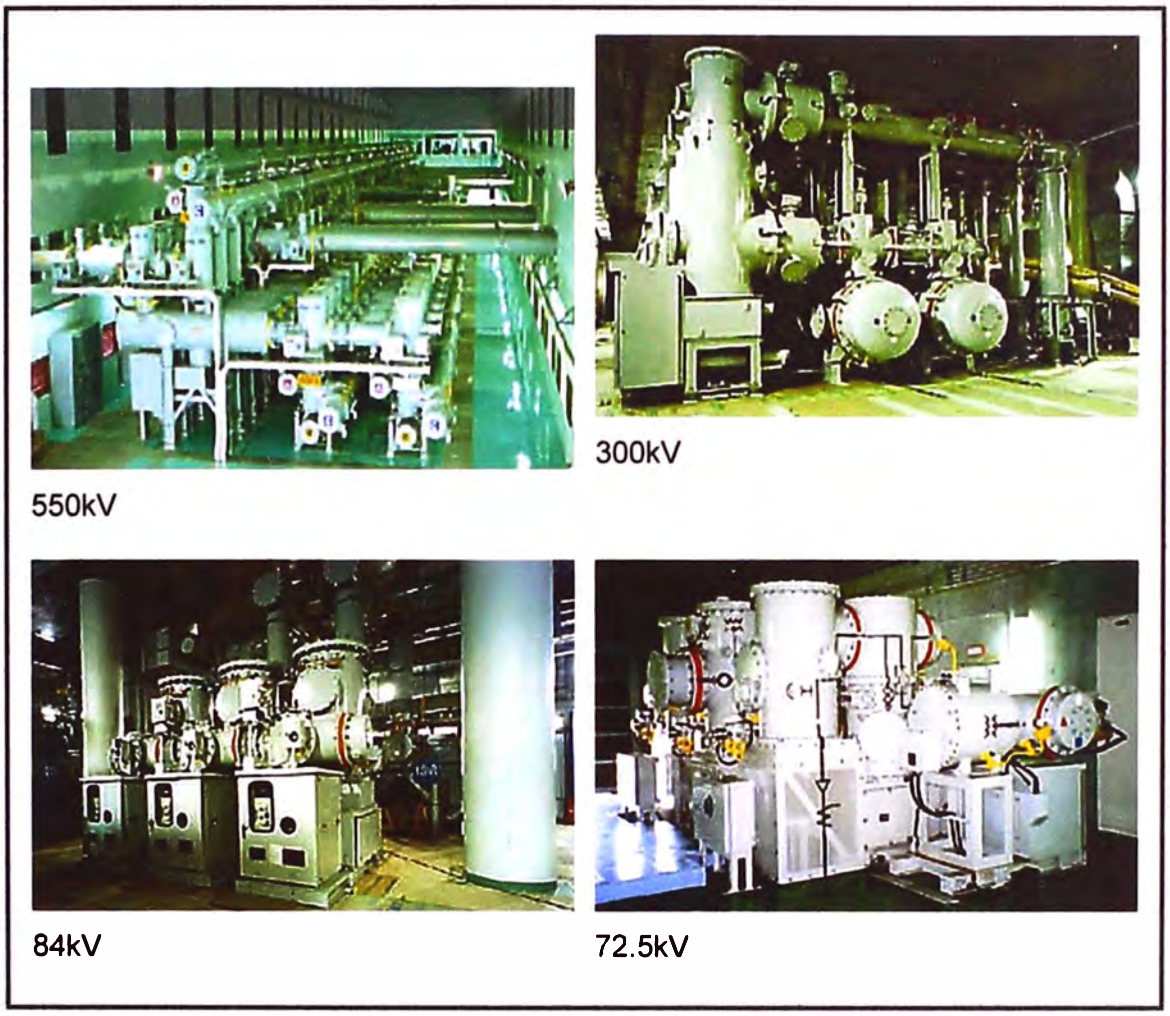


Figura 1.4 Instalaciones Aisladas en Gas SF6 – GIS (Gas Insulated Switchgear)

Figura 1.5 Celdas C-GIS construidas según normas VDE para media tensión 36kV

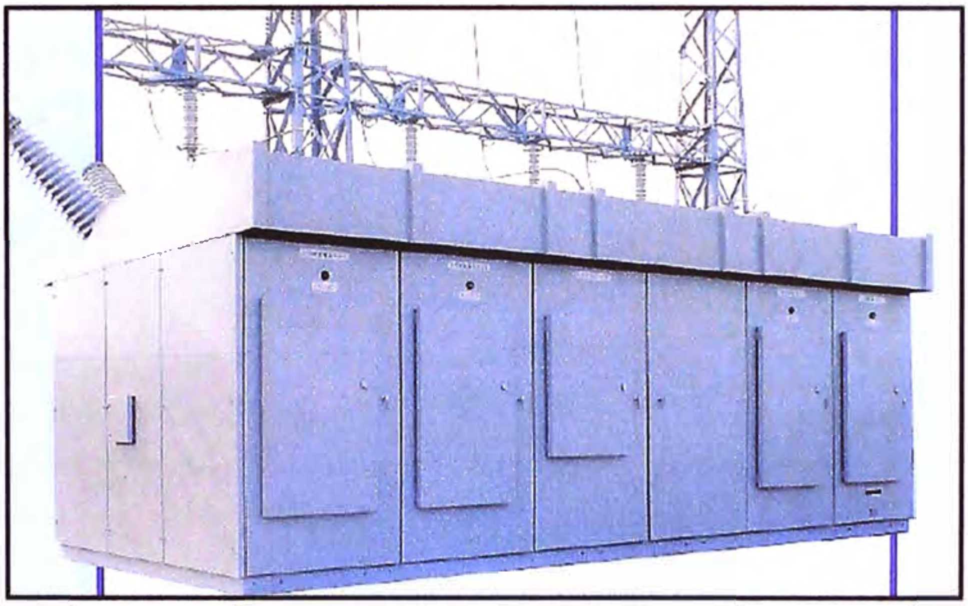


Figura 1.6 Celdas C-GIS montadas en un patio, en 72,5kV

1.4 Interruptores en SF6 vs Vacío

Hasta hace algunos años, la mayoría de fabricantes de interruptores de media tensión y algunos estudiosos del tema, dedicaron varios trabajos en comparar las dos tecnologías vigentes para la interrupción del arco eléctrico, el SF6 y el vacío. Independientemente de los adeptos que generó una y otra tecnología, llegó un momento en que, con el perfeccionamiento del interruptor en vacío, que tuvo al comienzo hubo muchas dificultades, tanto el interruptor de vacío como el de SF6 tuvieron igual aceptación y la lucha de los mercados se centró fundamentalmente en el precio.

. Podría decirse que para media tensión, si un interruptor estaba correctamente dimensionado, no existían diferencias técnicas que realmente hicieran sobresalir uno u otro tipo de interruptor. Los problemas de pérdida o falla del vacío, así como los de sobre tensiones o transitorios por maniobra, fueron temas gradualmente superados por los fabricantes, hasta que llegó un momento en que los fabricantes presentaron ambos tipos de interruptores, vacío y SF6, como soluciones equivalentes, sin preferencia por alguno de ellos.

Un aspecto concurrente que ha terminado de gravitar a favor del posicionamiento del interruptor en vacío es el tema ecológico. A partir del año 1998, tras la suscripción el Protocolo de Kyoto, se dio inicio a la lucha contra el calentamiento del planeta y entraron en vigor los objetivos obligatorios de limitación y reducción de gases de efecto invernadero, entre los que figura el hexafluoruro de azufre (SF6). Desde entonces, la mayoría de los fabricantes han concentrado su trabajo en torno al interruptor de vacío y hoy en día son muy pocos los que aun mantienen la fabricación de interruptores en SF6, quienes a pesar de haber introducido algunos cambios en el diseño, como por ejemplo botellas selladas para evitar fugas de gas, no han revertido una tendencia hacia la tecnología del vacío a nivel mundial.

Cabe señalar que hasta antes de que se diera este hecho, las comparaciones en media tensión eran pertinentes, incluso considerando tecnologías ya superadas como la de pequeño volumen de aceite y aire comprimido. El aceite con obvias desventajas de un alto costo de mantenimiento y flamabilidad, mientras que el aire con soluciones costosas y pesadas, quedaron rápidamente a la saga, dejando libre el camino para los interruptores en vacío y SF6, que habían incursionado casi simultáneamente al mercado.

Lo que sigue es una presentación general de ambos interruptores en media tensión, seguida de una comparación técnica entre ambas tecnologías.

1.4.1 Interruptores de Vacío en Media Tensión

En un interruptor de vacío, las cámaras de interrupción o botellas de vacío son empleadas para la apertura y cierre de corrientes de falla o de carga. En el momento que los contactos del interruptor se separan físicamente, la corriente a ser interrumpida da inicio a la descarga del arco con la vaporización del metal de los contactos y fluye a través del plasma hasta el próximo paso de la corriente por cero. El arco es luego extinguido y los vapores de metal condensados en las superficies metálicas en cuestión de microsegundos.

Las propiedades del interruptor de vacío dependen básicamente del material y de la forma de los contactos. Durante la fase del desarrollo del interruptor se probaron varios tipos de material para los contactos. A la fecha se considera que una aleación de cobre cromo, libre de oxigeno, es el mejor material. En esta aleación el cromo es distribuido en el cobre en la forma de granos muy finos. Este material combina, una buena característica de extinción del arco, con una tendencia reducida a que se suelden los contactos.

Con una corriente de falla inferior a los 10kA, el arco se presenta como una descarga difusa, mientras que con corrientes mayores el arco adquiere forma definida y localizada puntualmente en el ánodo. Un arco así definido por mucho tiempo puede fatigar térmicamente los contactos, al punto de que ya no es posible garantizar la desionización de la zona de contacto, cuando la corriente pasa por cero. Para resolver este problema la raíz del arco debe moverse sobre la superficie del contacto. En tal sentido, los contactos poseen una forma tal que la corriente que fluye a través de ellos produce un campo magnético, que esta a 90° con el eje del arco. Este campo radial hace que la raíz del arco rote rápidamente alrededor del contacto, produciéndose una distribución uniforme del calor sobre su superficie. Los contactos de este tipo son llamados electrodos de campo magnético radial y son usados en la mayoría de interruptores para media tensión.

También debe mencionarse otro diseño de interrupción de vacío, logrado posteriormente, mediante el manejo del arco a través de un campo magnético axial.

Dicho campo es obtenido al hacer pasar la corriente del arco a través de una bobina, dispuesta apropiadamente en el exterior de la cámara de interrupción.

1.4.2 Interruptores de SF6 en Media Tensión

En los interruptores en SF6, luego de que los contactos se han separado, la corriente sigue fluyendo a través del arco, cuyo plasma consiste en gas SF6 ionizado. Mientras dura el arco, éste es sometido a un flujo constante de gas que lo refrigera extrayéndole el calor. El arco es extinguido en el paso de la corriente por cero. El flujo continúo del gas desioniza el espacio entre contactos y establece la rigidez dieléctrica necesaria para evitar el reencendido.

La dirección del flujo del gas, es decir si es paralelo o transversal al eje del arco tiene una influencia decisiva en la eficiencia del proceso de interrupción del arco. Las investigaciones han demostrado que un flujo de gas en la dirección axial crea una turbulencia que causa una intensa y continua interacción entre el gas y el plasma mientras la corriente se acerca a cero. Por otro lado, un flujo de gas cruzado para refrigerar el arco, se consigue por lo general moviendo el arco en el gas estacionario. Este proceso de interrupción puede, sin embargo, hacer que el arco se vuelva inestable y en consecuencia resulten grandes fluctuaciones en la capacidad de interrupción del interruptor. Para conseguir el flujo axial al arco se necesita crear una presión diferencial a lo largo del arco. La primera generación de los interruptores en SF6 utilizó el principio de las dos presiones del interruptor de soplo en aire. Aquí se debía almacenar una cantidad de gas bajo alta presión y se liberaba en la cámara de extinción. Con la segunda generación se eliminó el empleo del gas a presión y su compresor asociado. En este caso la presión diferencial fue creada por un pistón unido al contacto móvil, que comprimía el gas en un pequeño cilindro al momento de apertura de los contactos. Esta técnica fue denominada "puffer". La desventaja de este diseño fue la necesidad de un mecanismo de accionamiento relativamente muy potente.

Ninguno de los dos diseños mencionados fue lo suficientemente económico y capaz de competir en el mercado, todavía dominado por los interruptores en aceite. Debido a que el mecanismo de mando, era el componente de mayor costo en el interruptor tipo puffer, hubo innumerables desarrollos con el objeto de reducir o eliminar dicho factor de sobrecosto.

Uno de estos desarrollos se concentró en emplear la propia energía del arco, para crear directamente la presión diferencial que se necesitaba. La técnica resultante se llamó auto soplado o tercera generación, en la cual la sobrepresión es creada mediante la energía del arco al calentar el gas bajo condiciones controladas.

Durante las primeras fases de este desarrollo, para asegurar la adecuada interrupción de pequeñas corrientes, se utilizó un pistón adicional en el mecanismo de interrupción. Las sucesivas mejoras del diseño eliminaron este requerimiento y en los últimos diseños los mandos solo tienen que proveer la energía necesaria para la apertura de los contactos.

De manera simultánea, con el desarrollo del interruptor de autosoplado, surgió otro diseño, el interruptor en SF6 con arco rotativo. En este diseño, el arco es forzado a desplazarse en medio del gas estacionario. El movimiento relativo entre el arco y el gas no es más axial sino más bien radial, es decir cruzado. La energía para el mando en este tipo de interruptor también es mínima.

1.4.3 Tabla Comparativa de Interruptores en SF6 y Vacío

	Interruptor en SF6		Interruptor en Vació
Criterios	Cámara de Interrupción (Puffer Circuit Breaker)	Interruptor camara autopresurizada (Self-pressuring circuit-breaker)	Material del contacto Cobre-cromo
Requerimientos de Energía para operación	Los requerimientos de Energía para operación son altos debido al gran mecanismo que suministra la energía necesaria para comprimir el gas.	Los requerimientos de Energía para operación son bajos debido que el gran mecanismo mueve solo masas pequeñas a una velocidad moderada sobre cortas distancias. El mecanismo no prevee la energía para crear el flujo del gas.	Los requerimientos de Energías son muy bajos debido a que el gran mecanismo mueve solo relativamente masas pequeñas a moderada velocidad sobre muy cortas distancias.

<table>
<tr><td>Energía de Arco</td><td colspan="2">Debido a la alta conductibilidad del arco en Gas SF6, La disipación de energía en el arco es bajo (tensión entre arco es de 150 a 200 V</td><td>Por que la tension es muy baja frente al arco de energía de vapor de metal es muy bajo (Arco de Voltaje esta entre 50 y 100 V)</td></tr>
<tr><td>Erosión en el Contacto</td><td colspan="2">Debido a que la baja energía la erosión del contacto es muy pequeña. Due to the low energy the contact erosion is small.</td><td>Debido a la baja energia de arco, el rapido movimiento de la raiz del arco sobre los contactos y por lo tanto los vapores de metal se recondensan sobre los contactos, la erosion es extremadamente pequeña.</td></tr>
<tr><td>Medio de Extinción de Arco</td><td colspan="2">El elemento gaseoso SF6 posee excelentes propiedades dieléctricas y de extinción de arcos. Después de la extinción de arco, las moléculas de gas disociados se recombinan casi completamente para reformar el SF6. Esto significa que prácticamente no ocurre perdida/consumo del medio de extinción. La presión de gas puede ser verificada de una forma permanente y muy simple. Esta función no es necesaria donde los interruptores son sellados de por vida.</td><td>No se requiere ningún medio de extinción adicional. El medio de extinción en Vacío es ideal a presiones de 10-7 Bars o menos. Los interruptores son “Sellados de por vida” por lo tanto la supervisión del cámaras de vació no son requeridas.</td></tr>
<tr><td>Comportamiento de la interrupción en relación a la corriente de corte.</td><td>La presión se incrementa por lo tanto el flujo de gas es independiente del valor de la corriente. Corrientes grandes o pequeñas son tratadas con la misma intensidad. Solo pequeños valores de grandes frecuencias, corrientes transitorias, cualquiera, serán interrumpidas. La des-ionización del contacto de vacío se produce muy rápido, debido a la característica electro-negativa del gas SF6 y los productos del arco eléctrico.</td><td>La presión se incrementa por lo tanto el flujo de gas es dependiente en el valor de la corriente a ser interrumpida. Grandes corrientes son tratadas intensamente, pequeñas corrientes son tratadas suavemente. Corrientes transitorias de Altas frecuencias no, en general, serán interrumpidas. La des-ionización del contacto de vacío se produce muy rápido, debido a la característica electro-</td><td>Ningún flujo de un medio de extinción es requerido para extinguir el arco en la cámara de vacío. Una extrema rápida des-ionización de los contactos de vacío, garantizan la interrupción de todas las corrientes aún sean grandes o pequeñas. Corrientes transitorias de altas frecuencias pueden ser interrumpidas. El valor de la corriente de corte es determinada por un tipo de material de contacto usado.</td></tr>
</table>

		negativa del gas SF6 y los productos.	
No. de operaciones de corto circuito	10---50	10---50	30---100
No. de operaciones a plena carga	5000---10000	5000---10000	10000---20000
No. de operaciones mecanicas	5000---20000	5000---20000	10000---30000

Tabla 1.2 Comparación de Tecnologías en SF6 y Vacío.

1.4.4 Interruptores en SF6 y Vacío en Alta Tensión

De momento, en el campo de alta tensión, aun cuando ya existen interruptores de vacío en tensiones hasta 145 kV, no se puede afirmar que estemos frente a una competencia entre la tecnología del SF6 y la del vacío.

Lo que es importante resaltar con respecto al vacío, es que en alta tensión se han logrado avances notables y ya hay soluciones concretas, como por ejemplo, las celdas C-GIS de Toshiba en 60kV, y también los interruptores VCB para intemperie, de tanque muerto, de Japan AE Power Systems Corporation para 72,5kV. A nivel de Europa se sabe que Siemens viene trabajando intensamente en este campo, al igual que ABB.

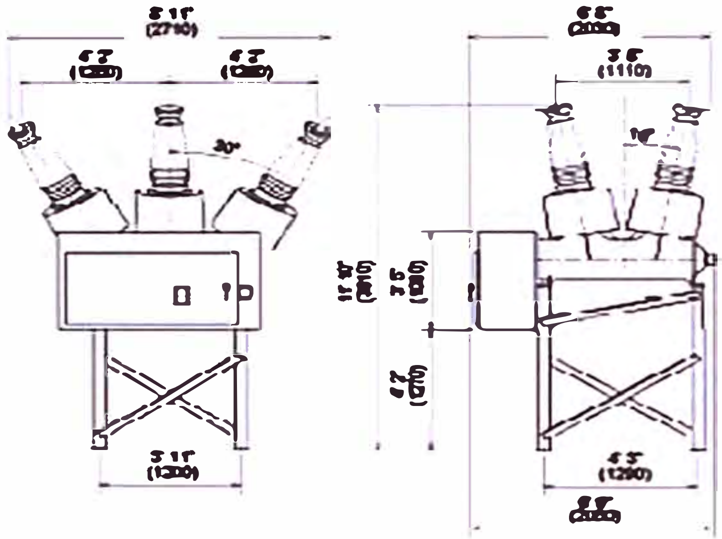
Los problemas técnicos de los interruptores en vacío con la alta tensión, tales como el tamaño de las botellas de vacío, las limitaciones del dieléctrico, la inseguridad frente a la emisión de rayos X y otros más, propios del diseño, han sido superados y hoy se comercializa soluciones de vacío en 72.5kV, como lo vemos en los catálogos que acompañan este trabajo.

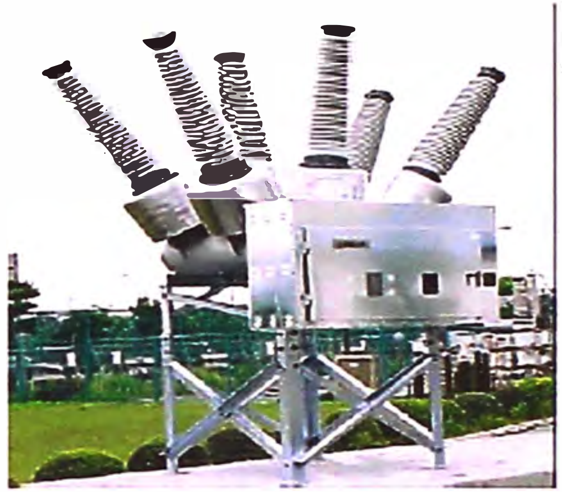
Hoy en día gracias al progreso mencionado, la industria japonesa ha ido más lejos aun y ha empezado a fabricar los interruptores con cámara de vacío y aislamiento complementario con aire comprimido seco, en lugar del SF6 que se venía utilizando hasta hace poco. Se trata de una nueva generación de equipos que, no emplean más el SF6 y por lo tanto serán absolutamente amigables con el medio ambiente. Se adjunta al final de este capítulo un catálogo reciente de la empresa HVB AE Power Systems, correspondiente a un interruptor en vacío, del tipo tanque muerto para 72,5kV, que no emplea gas SF6.

72.5 kV Dry Air Insulated Dead Tank Type VCB

Features

- **No usage of SF6 gas**
- **Longer life & Easier maintenance than GCB**





Rated voltage [kV]	72.5
Rated current [A]	1250/2000
Rated breaking current pkA]	31.5
CB operating mechanism	Motor charged spring
Insulation medium	Compressed air
Rated dry air pressure [psig/Mpa]	72.5/0.5
Applicable standard	ANSI C37.06/IEC

CAPITULO II

CONFIABILIDAD EN SUBESTACIONES ELECTRICAS

2.1 Preliminar

Una de las tareas de la ingeniería eléctrica moderna, es el desarrollo e implementación de nuevas tecnologías en el diseño y fabricación de equipos, En particular, tratándose de equipos de potencia para subestaciones, el objetivo principal es reducir los costos de prevención de fallas, a través del incremento de la confiabilidad de los equipos. Además de ello hay un trabajo constante en extender la vida útil, disminuir su costo y atenuar cada vez más su impacto en el medio ambiente. Todo ello en aras de que los sistemas eléctricos brinden un servicio continuo y de calidad.

Los Sistemas Eléctricos de Potencia tienen varios componentes y cada uno con características singulares, y éstos forman parte importante de todo el sistema, cumpliendo cada uno con sus funciones específicas, diferentes de los demás componentes, pero importantes para el buen funcionamiento del sistema, tanto en condiciones de calidad como de continuidad de servicio. Uno de estos componentes son las subestaciones, cuya función es la interconectar circuitos entre sí, con las mismas características de potencia.

2.2 Definición de Confiabilidad

Académicamente la confiabilidad se puede definir como la capacidad de un producto de realizar su función de la manera prevista. Más ampliamente, la confiabilidad se puede definir como la probabilidad de que un producto cumpla su función, de acuerdo a lo previsto, sin incidentes, por un periodo de tiempo especificado y bajo condiciones indicadas.

La ejecución de un análisis de confiabilidad en un producto o un sistema implica una serie de exámenes para determinar cuan confiable es el producto o sistema que pretende analizarse. Una vez realizados los análisis, es posible prever los efectos de los cambios y de las correcciones del diseño para mejorar la confiabilidad.

Los diversos estudios del producto se relacionan, vinculan y examinan conjuntamente, para poder determinar la confiabilidad del mismo bajo todas las perspectivas posibles, determinando problemas potenciales y poder sugerir correcciones, cambios y/o mejoras en productos o elementos.

2.3 Mantenimiento en Subestaciones

Al buscar una filosofía aplicable al mantenimiento en subestaciones, se puede encontrar que orientar el mantenimiento hacia la Disponibilidad de Equipos, es la más ajustable a los requerimientos y características de los Sistemas Eléctricos de Potencia. Esta orientación debe estar basada, tal vez, en los argumentos más utilizables de la filosofía del Mantenimiento Productivo Total (TPM) y del Mantenimiento basado en la Confiabilidad (RCM). Antes de hablar de los argumentos más aplicables al Mantenimiento en subestaciones, tal vez sea necesario mencionar por qué ambos tipos de mantenimiento, no son directamente aplicables a subestaciones, es decir cada uno por sí solo y completamente, aplicado a subestaciones.

El TPM es una filosofía de mantenimiento que exige Calidad Total en el trabajo de mantenimiento, lo cual no es difícil de obtener, pero en consecuencia exige que en los sistemas en los que se aplica esta filosofía, llegar al nivel de "cero fallas"; sabiendo que en sistemas de potencia la mayor parte de las fallas se deben a factores externos, muchas veces que escapan al control (descargas atmosféricas, por ejemplo), no será posible llegar al nivel de "cero fallas", sin elevar considerablemente los costos de operación, y por ende el costo de la energía.

Por otro lado, el RCM es un sistema de mantenimiento que se basa en la Confiabilidad, es decir que el sistema, en el que se aplica el RCM, debe continuar con su trabajo normal a pesar del surgimiento de alguna falla y de la falta de algún componente del sistema, y esto se logra mediante el reemplazo de dicho componente en el sistema productivo, sin importar si este reemplazo es similar o no, el punto es que el sistema mantenga su ritmo de producción. Se sabe que una subestación tiene la función de transmitir la energía eléctrica de un sistema a otro, y que cada componente de la misma cumple funciones únicas relativas a ese equipo, por tanto, en caso de ausencia de uno de estos, sin importar la causa, no será posible reemplazar u obviar tal componente para que la transmisión de energía continúe porque esto podría llevar a fallas mayores, o paradas del sistema, que pudieron haberse evitado si el componente en cuestión hubiera estado cumpliendo sus funciones.

Pero esto no descarta a los tipos de mantenimiento mencionados para su aplicación en subestaciones, cabe mencionar que el RCM puede formar parte del TPM aplicado a un sistema productivo; si se analiza, el TPM es una filosofía que se refiere más al recurso humano del mantenimiento, y su comportamiento en el desarrollo de dicha función, que al sistema productivo en sí, y el RCM se inclina más al sistema productivo y su confiabilidad. Por tanto, estos argumentos pueden ser aplicables a cualquier sistema incluyendo subestaciones.

Esto lleva a buscar la confiabilidad de una subestación y, según lo antes mencionado, para lograr esto deberá buscarse la Disponibilidad de los Equipos de la misma, ya que "equipos disponibles cumplen su función y por tanto el sistema será confiable". Para que los equipos estén disponibles, el mantenimiento preventivo jugará un papel importante, dejando de ese modo, la posibilidad de fallas debidas principalmente a factores externos, es donde el mantenimiento correctivo deberá jugar su papel, y para el buen desempeño de estos mantenimientos, el personal deberá comportarse con seguridad, orden y disciplina necesarios, y es donde el TPM se aplica.

2.4 Factores Universales

En la práctica, la confiabilidad puede apreciarse por el estado que guardan o el comportamiento que tienen cinco factores llamados universales y que se consideran propias en todo recurso por conservar; estos factores son los siguientes:

1. Edad del equipo
2. Medio ambiente en donde opera
3. Carga de trabajo
4. Apariencia física.
5. Mediciones o pruebas de funcionamiento

De manera general, para determinar la confiabilidad de un producto, éste se somete a diversos estudios, los cuales se relacionan, vinculan y examinan conjuntamente, bajo todas las perspectivas posibles, determinando posibles problemas, para luego, poder sugerir correcciones, cambios y/o mejoras en productos o elementos.

La disminución ó pérdida de la función de un componente con respecto a las necesidades de operación, que se requieren para un momento determinado, se denomina falla. Esta condición puede interrumpir la continuidad o secuencia ordenada de un proceso, donde ocurren una serie de eventos que tienen más de una causa. Existen dos tipos de falla, las cuales son explicadas a continuación:

Falla funcional o incapacidad de cualquier elemento físico de satisfacer un criterio de funcionamiento deseado. Por ejemplo, un equipo deja de funcionar totalmente.

Fallas parciales (potenciales) son las condiciones físicas identificables que indican que va a ocurrir una falla funcional. Estas fallas están por encima o por debajo de los parámetros identificados para cada función. Por ejemplo, el elemento no cumple un estándar o parámetro establecido de su servicio.

2.4.1 Aplicación de los Factores Universales

El siguiente es un ejemplo de evaluación de la confiabilidad en una subestación, para un transformador de 1000kVA, instalado en una subestación industrial y que viene presentando pérdida en el nivel de asilamiento. Para ello se ha preparado, en base a estos cinco factores, un "transformador patrón", para después compararlo con el transformador que queremos clasificar; y de ese modo determinar si debe o no rehabilitarse y, en este último caso conocer hasta qué grado de confiabilidad se conseguiría llevarlo.

Tabla 2.1 Aplicación de los Factores Universales

Factor	Confiabilidad en %			
	Transformador Ideal	Transformador Existente	Transformador con rehabilitación	Compra de nuevo transformador
Mediciones o pruebas	40	4	40	40
Carga de trabajo	25	25	25	25
Edad	15	6	10	15
Apariencia física	10	9	10	10
Medio ambiente	10	5.6	5.6	9.6
Totales	100	49.6	90.6	99.6

Por lo anterior es posible concluir que se llega a un grado de confiabilidad muy alto rehabilitando el transformador existente, con una confiabilidad de 90.6%, sin necesidad de adquirir un transformador nuevo, ya que en ambos casos se tendría una mejora del 100 %, tanto en el factor de mediciones o pruebas, como en de apariencia física. Obviamente el factor que no se puede mejorar con este enfoque es el del medio ambiente,

Debe quedar claro, sin embargo, que en el caso de comprar un nuevo equipo se mejoraría no solo el factor de edad y sino la posibilidad de comprar un transformador con mayor rendimiento o más adecuado a las necesidades propias.

Habiendo encontrado que la confiabilidad del equipo rehabilitado y del equipo nuevo tienen valores muy cercanos, la decisión entre comprar un equipo nuevo o rehabilitar el existente dependerá casi exclusivamente del costo. El ejemplo que hasta aquí se ha visto, puede ser aplicado a cualquier otro tipo de recurso, solamente estudiando los cinco factores universales con respecto a lo que se desea calificar.

2.5 Confiabilidad en Subestaciones

Al diseñar una subestación, vista como un sistema eléctrico, deben tomarse en cuanta los siguientes aspectos relacionados con su confiabilidad:

1. Elevada confiabilidad de cada elemento del sistema. La confiabilidad del sistema está vinculada con la confiabilidad de cada elemento del sistema.
2. Resilencia. En lo posible, la falla de un elemento no debiera dejar todo el sistema sin funcionar.
3. Mantenibilidad. Un adecuad mantenimiento de los sistemas eléctricos al menos mantiene su confiabilidad en los valores de diseño de la instalación. Por el contrario, un mantenimiento no realizado o realizado en mala forma disminuye la confiabilidad del sistema.
4. Capacidad del sistema. El sistema debe estar diseñado para os consumos que abastecerá, con una capacidad de sobrecarga transitoria.
5. Flexibilidad. El sistema debe ser flexible y prever que existirán aumentos del consumo, o un cambio en la ubicación de estos oque existirán cambios tecnológicos que requerirán de un sistema distinto del que fue proyectado inicialmente. En este escenario, las modificaciones del sistema deben ser relativamente fáciles de realizar sin que el sistema pierda confiabilidad.

6. Interfaz adecuada con la infraestructura existente.

Complementariamente deberán considerarse las siguientes opciones que mejoran la confiabilidad de una subestación.

1. El uso de esquemas preferentemente modulares en lugar de un solo esquema central.
2. El empleo de equipos de reserva y de reemplazo para alimentar cargas críticas.
3. El diseño de sistemas en paralelo (esquemas de doble circuito).

2.6 Cálculo de la Confiabilidad

La confiabilidad, a nivel de sistemas eléctricos tanto en transmisión como en distribución, es un área de intensa investigación a nivel mundial debido a lo siguiente:

- La sociedad es muy sensible a las interrupciones en el suministro de electricidad, debido a la alta dependencia con este insumo en todas lás actividades de la vida diaria.
- Más del 90% del total de eventos de salida del sistema ocurren a nivel de distribución.
- Las normas de regulación establecen límites máximos para los indicadores de confiabilidad del servicio y consecuentemente debe enfrentarse a las eventuales penalidades y a la obligación de compensar económicamente a los usuarios.

Para hacer frente a este requerimiento han surgido en el mercado herramientas especiales de cálculo diseñadas para ayudar en la evaluación de la confiabilidad en redes y subestaciones. Un programa típico calcula una serie de índices de confiabilidad del sistema global y también calcula los índices relacionados con los clientes, como la frecuencia de las interrupciones, la duración, el número de clientes afectados, la carga promedio y la energía no suministrada.

La evaluación de la confiabilidad se ha convertido en los últimos años en un aspecto importante para los planificadores de sistemas eléctricos. El deseo de mejorar la confiabilidad del servicio puede originarse de nuevas reglamentaciones o de la competencia en el mercado. El ofrecer un servicio superior a un precio más atractivo es en beneficio tanto de la empresa eléctrica como del cliente.

CAPITULO III

CELDAS METALICAS C-GIS EN 60kV

3.1 Generalidades

Las normas técnicas correspondientes a las celdas en 60kV, tipo C-GIS, están establecidas en una norma particular del Japón, JEM1425, la cual se caracteriza por cumplir de manera general con las normas IEC 60298 e IEC 60694, aplicables a celdas metálicas (metal-clad) encapsuladas en gas. Por lo demás, debido a su naturaleza constructiva, las celdas metálicas para alta tensión son también diseñadas y construidas a prueba de arco interno.

El siguiente listado de normas corresponde a la ejecución de celdas para media tensión, tipo C-GIS, según IEC y DIN VDE en Alemania:

IEC 60298 (1996), German edition VDE 0670 Part 6 (1998)

IEC 60694 (1996), German edition VDE 0670 Part 1000 (1998)

DIN VDE 0101 (2000)

En general, las celdas metálicas C-GIS en 60Kv, son previstas para su instalación a la intemperie, pero también pueden ser montadas al interior, con la ventaja de reducir al mínimo su mantenimiento, pero requiriendo de la obra civil o edificio, que a su vez significara una mayor área de terreno,

Tabla 3.1 Celdas encapsuladas en gas SF6 (C-GIS)

TIPO		**72kV C-GIS**	**84kV C-GIS**
Tensión nominal		72kV	84kV
Tensión de prueba	al impulso	350kV	400kV
	a frecuencia industrial	140kV	160kV
Frecuencia nominal		50, 60Hz	50, 60Hz
Corriente nominal		800, 1250A	800, 1250A
Corriente de corta duración		20, 25, 31.5kA	20, 25, 31.5kA

3.2 Características y diseño

3.2.1 Características

Las características más importantes de las celdas metálicas C-GIS en 60kV son las siguientes:

1) Seguridad

Todo el equipamiento al interior de la celda, incluyendo el interruptor, el seccionador, los transformadores de corriente, los pararrayos, etc., se encuentra instalado en un cubículo metálico debidamente aterrado. Todas las partes vivas están protegidas por el gabinete metálico de acero, construido con paredes dobles. Las celdas C-GIS son diseñadas y fabricadas para una operación segura, libre de descargas eléctricas u otros accidentes.

2) Alta confiabilidad

Se trata de celdas metálicas debidamente compartimentadas en las cuales el equipo va montado. Las celdas C-GIS están construidas a prueba de tifones y terremotos. Además su acabado está previsto para soportar adecuadamente condiciones extremas del medio ambiente, la contaminación, la humedad y cuenta con elementos adecuados para evitar el ingreso de animales pequeños e insectos.

3) Empleo de Interruptores en Vacío (VCBs)

El empleo de interruptores en vacío de alta tensión en 60kV, brinda a las celdas C-GIS una alta confiabilidad y permite que los periodos de mantenimiento resulten considerablemente espaciados. Los interruptores de vacío están diseñados para un elevado número de operaciones y no requieren de válvula de control para la presión del gas.

4) Mínimo Mantenimiento

En general, las celdas C-GIS no demandan de un mantenimiento frecuente, pero además, su diseño es adecuado para que el mantenimiento periódico sea hecho fácilmente y en muy poco tiempo.

5) Contenido de baja presión de Gas SF6

El cubículo de las celdas C-GIS contiene gas SF6 a baja presión (cercana a la presión atmosférica). El gas a presión permite incrementar el aislamiento entre las partes vivas y mantener al íntegro de los equipos libres de humedad o de contaminación proveniente del medio ambiente.

6) Sistema de barra colectora aislada

La barra principal o colectora con asilamiento mediante XLPE, de fácil trabajo en el lugar de la instalación.

7) Compatibilidad de Instalación Intemperie / Interior

Las celdas C-GIS pueden ser instaladas a la intemperie o en interior bajo techo, dentro de un edificio.

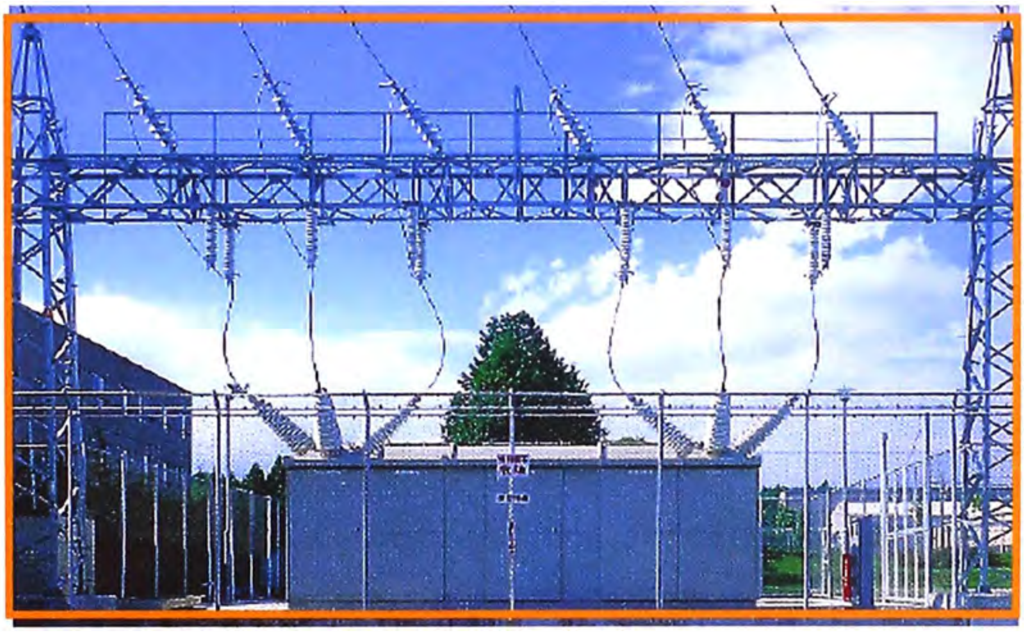


Fig. 3.1 Celdas C-GIS montadas en un patio, en 72,5kV

8) Ahorro de Espacio en la Instalación

Debido a lo compacto de su ejecución, las celdas C-GIS pueden ahorrar mucho espacio. Dependiendo del tamaño de la instalación, una subestación con celdas C-GIS puede llegar a requerir solo el 22% de lo que ocupa una instalación convencional con aislamiento en aire.

9) Instalación de Relés

Los relés de protección, los contadores de energia y otros elementos de control pueden ser instalados en cada una de las celdas, para lo cual cuentan con un compartimento de baja tensión.

3.2.2 Diseño de una celda típica

Instalación para montaje al interior o exterior

Fácil trabajo de instalación en el sitio, sin manipular gas SF6.

Ingreso de la tensión subterránea o aéreo.

Conexión al transformador mediante cable o ducto de barras.

Dispositivo para desconexión de los pararrayos durante los ensayos de tensión aplicada.

Posibilidad de expansión futura sin manipular gas SF6.

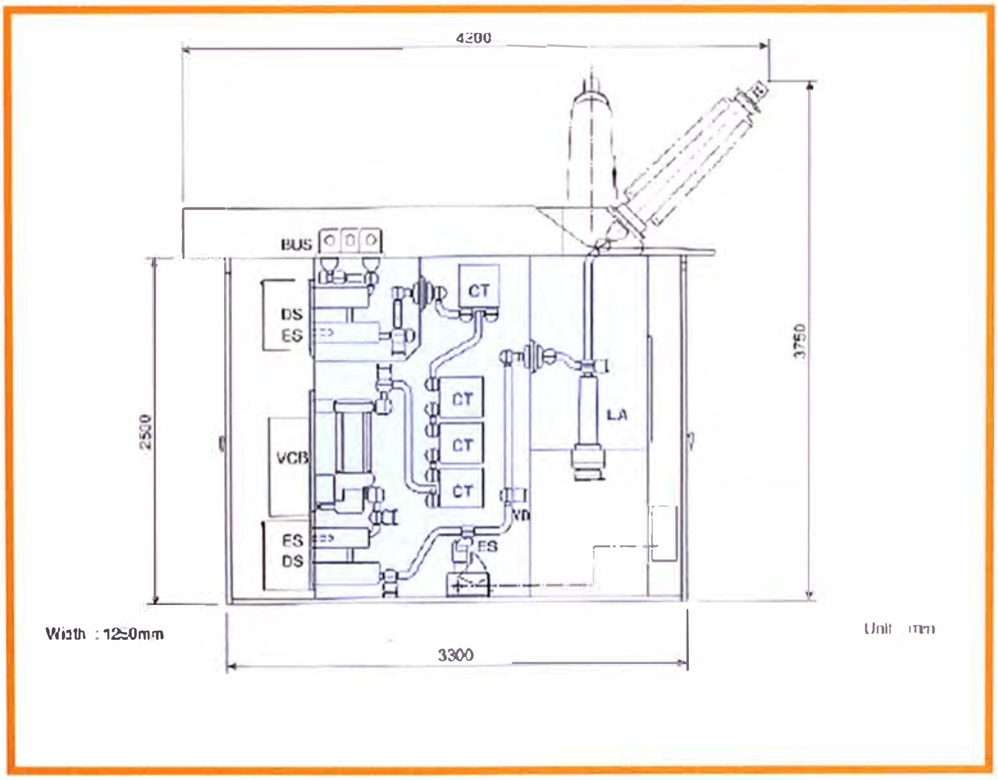


Fig. 3.2 Diseño de una celda típica

Leyenda:

VCB: Interruptor en vacío

DS: Seccionador

ES: Seccionador de puesta a tierra

CT: Transformador de Corriente

LA: Pararrayos

VD: Revelador de tensión

C: Contador de descargas

ID: Dispositivo de aislamiento

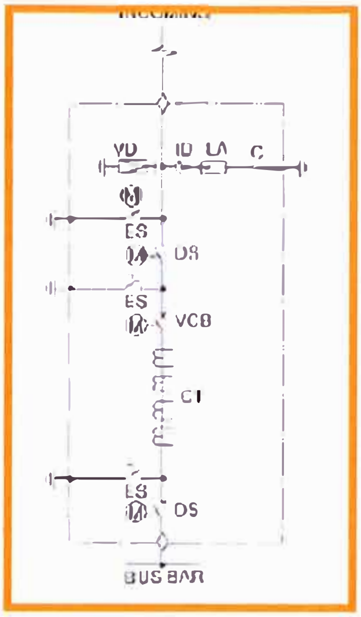


Fig.3.3 Leyenda

3.3 Especificaciones Técnicas

Fig.3.4 Celdas Modulares

3.3.1 Celda Modular C-GIS

Fig.3.5 Celda Modular C-GIS

Tabla 3.2 Celda Modular C-GIS

Modelo		**GF70**
Tensión del Sistema		66kV/69kV/70kV
Tensión Nominal		72kV/72.5kV
Nivel Básico de aislamiento	BIL	325kV/350kV
Tensión de ensayo	AC	140kV
Frecuencia Nominal		50Hz/60Hz
Corriente Nominal		800A/1250A
Corriente de Cortocircuito		25kA/31.5kA (1/2/3 sec.)
Presión de gas Nominal		0.05MPa (medido a 20° C)
Normas		IEC298, IEC694, JEM1425

3.3.2 Componentes Principales

(1) Interruptor en vacío (VCB)

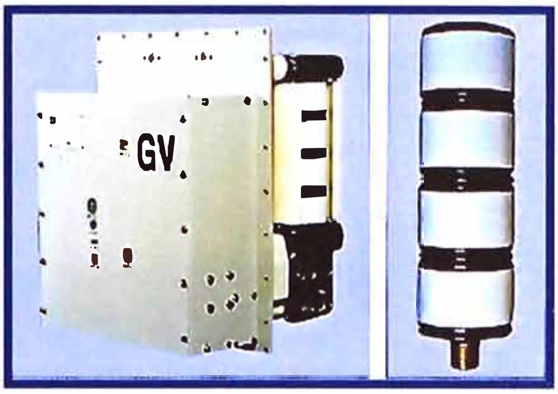


Fig.3.6 Interruptor en vacío (VCB)

Tabla 3.3 Interruptor en vació (VCB)

Modelo	GV-60/70K/M 25/32B
Tensión del Sistema	66kV/69kV/70kV
Tensión Nominal	72kV/72.5kV
Corriente Nominal	800A/1250A
Capacidad de Interrupción	25kA/31.5kA
Corriente de corto circuito	25KA/31.5kA (3 sec.)
Tiempo de interrupción	3 cycles
Mando	Motor y resortes (DC 110V)
Normas	IEC56, JEC2300

(2) Seccionador (DS) con cuchilla de puesta a tierra (ES)

Tabla 3.4 Seccionador (DS) con cuchilla de puesta a tierra (ES)

Modelo		GS-60/70K/M 25/32B
Tensión del Sistema		66kV/69kV/70kV
Tensión Nominal		72kV/72.5kV
Corriente Nominal		800A/1250A
Corriente de corto circuito		25KA/31.5kA (3 sec.)
Mando	DS	Eléctrico (DC 110V) y Manual almacenamiento de energía
	ES	Eléctrico (DC 110V) y Manual almacenamiento de energía
Normas		IEC129, JEC2310

Fig.3.7 Seccionador (DS) con cuchilla de puesta a tierra (ES)

(3) Transformador de Tensión (VT)

Encapsulado en resina expóxica (Unidad monofásica)

Tabla 3.5 Transformador de Tensión (VT)

Modelo	VZ-E60/70 B/C
Tensión del Sistema	66kV/69kV/77kV
Tensión Nominal	66/√3kV:110/√3V:110/3V 66/√3kV:115/√3V:110/3V 77/√3kV:110/√3V:110/3V
Consumo Nominal	220/200VA
Clase Precisión	1P/3G, 0.3Z, 1.0/3P
Normas	IEC186, ANSI C57.13 JEC1201

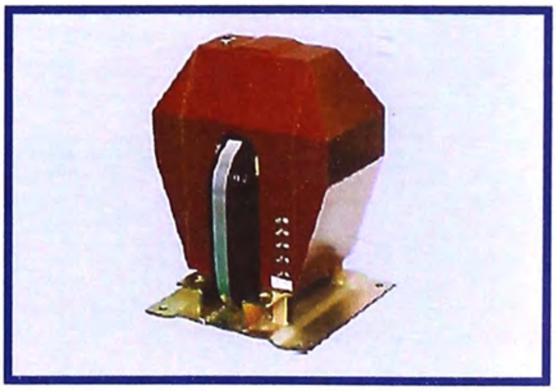


Fig. 3.8 Transformador de Tensión (VT)

(4) Transformador de Corriente (CT)

Encapsulado en resina expóxica (Tipo toroidal o bloque)

Tabla 3.6 Transformador de Corriente (CT)

Modelo	A-E60/70A, A-ECSG
Tensión del Sistema	66kV/69kV/77kV
Corriente Primaria Nominal	De acuerdo con la especificación
Corriente Secundaria Nominal	5A/1A
Consumo Nominal Clase Precisión	De acuerdo con la especificación
Normas	IEC185, ANSI C57.13 JEC1201

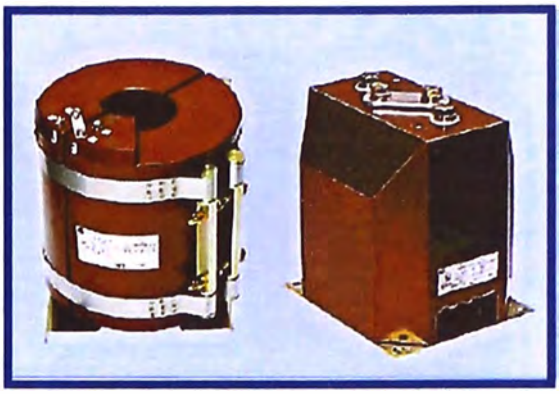


Fig. 3.9 Transformador de Corriente (CT)

(5) Pararrayos de Oxido Metálico, Tipo estación

Tabla 3.7 Pararrayo de Oxido Metálico, Tipo estación

Modelo	RVLRB-72CY,RVLMC-84C1Y, RVLMC-98C1Y
Tensión del Sistema	66kV/69kV/77kV
Tensión Nominal	72kV/72.5kV
Corriente Descarga nominal	10kA (Clase Estación)
Normas	IEC60099-4, JEC217

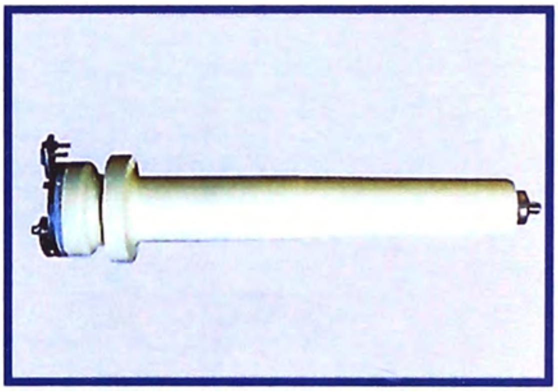


Fig. 3.10 Pararrayo de Oxido Metálico, Tipo estación

(6) Barra Principal o Colectora

Aislamiento mediante XLPE

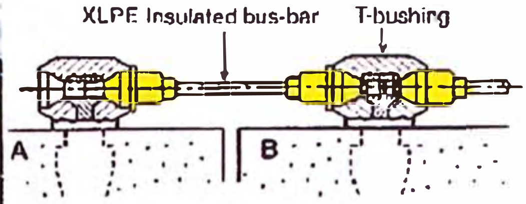


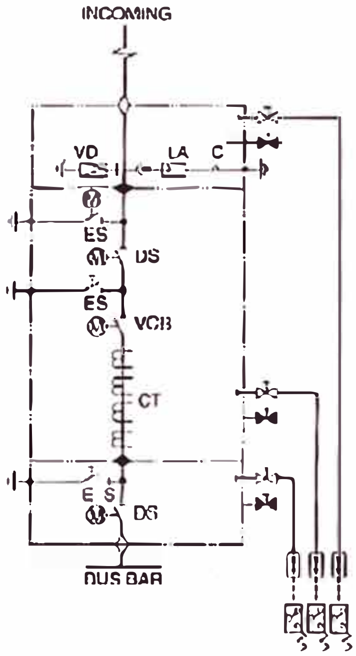
Fig. 3.11 Barra Principal o Colectora

(7) Conexionado de celdas a transformador mediante ducto de barras segregadas

Fig 3.12 Conexionado de celdas a transformador mediante ducto de Barras segregada

(8) Sistema de monitoreo de gas SF6

Se instala un switch de densidad por cada compartimiento y se monitorea la presión del gas



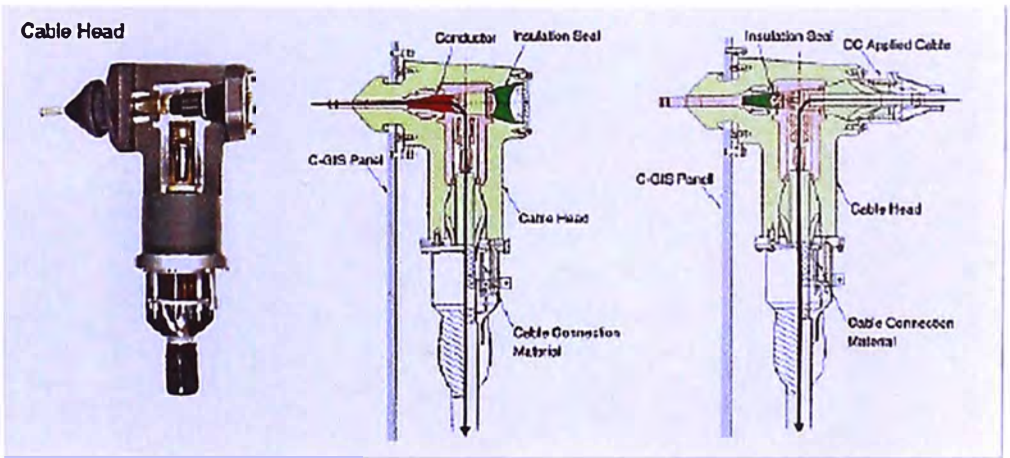
Presión Nominal	Alarma de baja presión
0.05MPa a 20°C	0.03MPa a 20°C

Fig. 3.13 Sistema de monitoreo de gas SF6

Densímetro y switch de densidad

(9) Prueba del cable de tensión aplicada en el sitio

La prueba del cable con tensión aplicada es posible sin manipular el gas SF6 en el sitio.



Cable head outline — Nominal operation — Withstand voltage test of power cable

Fig. 3.14 Prueba del cable de tensión aplicada en el sitio

3.4 Tipos de Instalación

1. **Instalación a la intemperie**

   Dos (2) llegadas aéreas y dos (2) alimentadores

Fig. 3.15 Instalación a la Intemperie

2. **Instalación al interior**

   Una (1) llegada por cable y dos (2) alimentadores

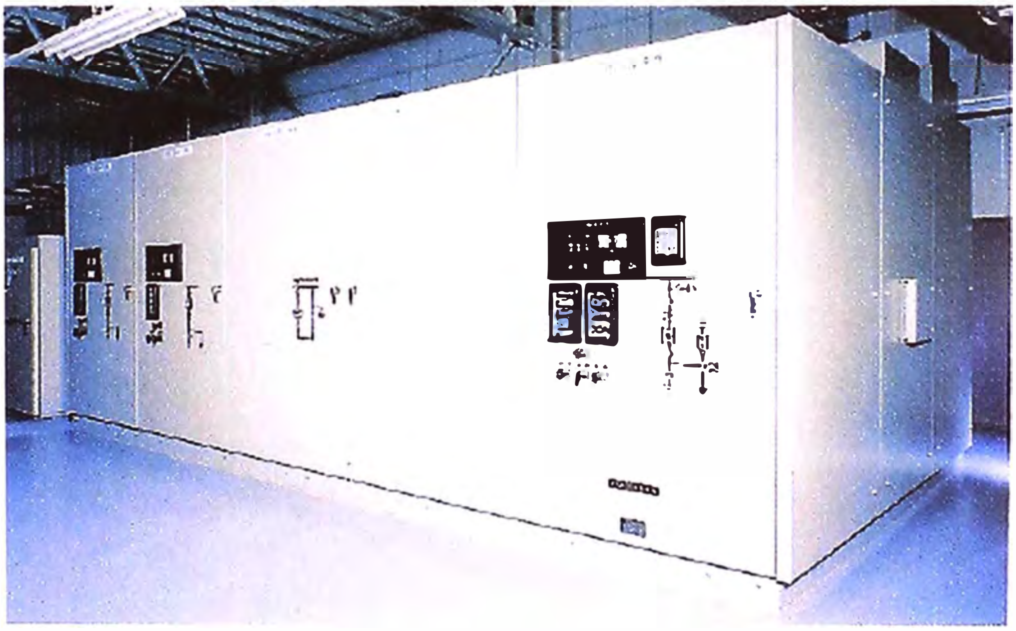


Fig. 3.16 Instalación al interior

3.5 Aplicaciones y Esquemas Unificares

APLICACIÓN

(1) Una llegada doble una unidad de medida y un alimentador.

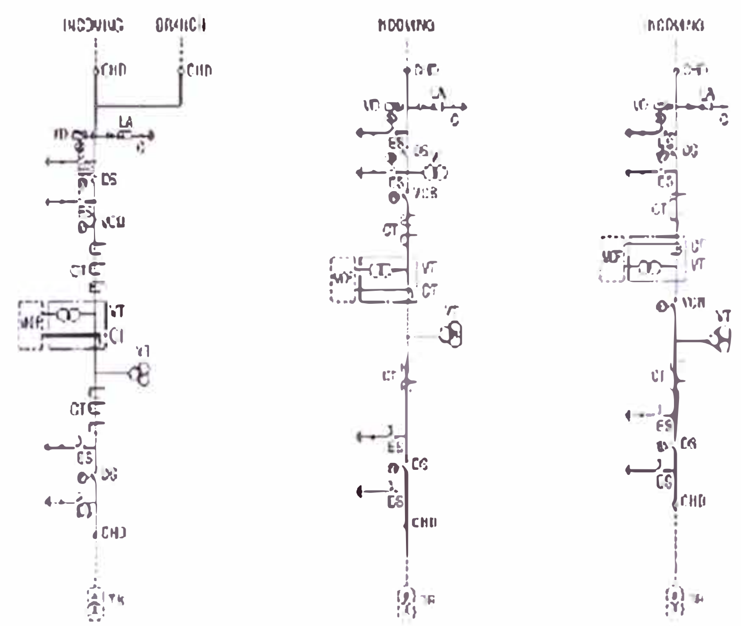


Fig.3.17 Esquema Unifilar Caso (1)

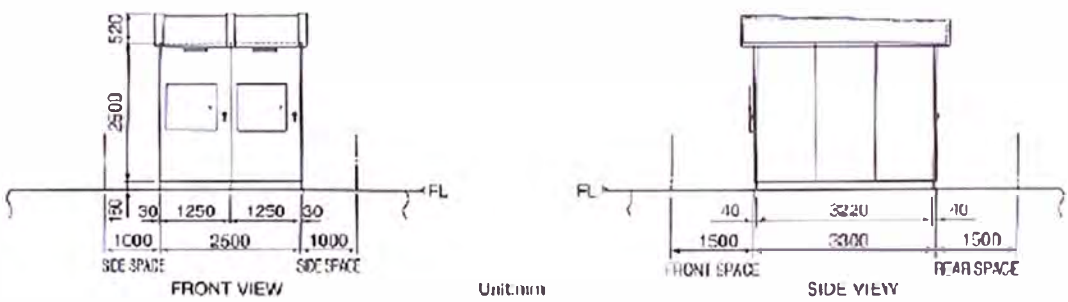


Fig.3.18 Dimensiones de Tipo Exterior

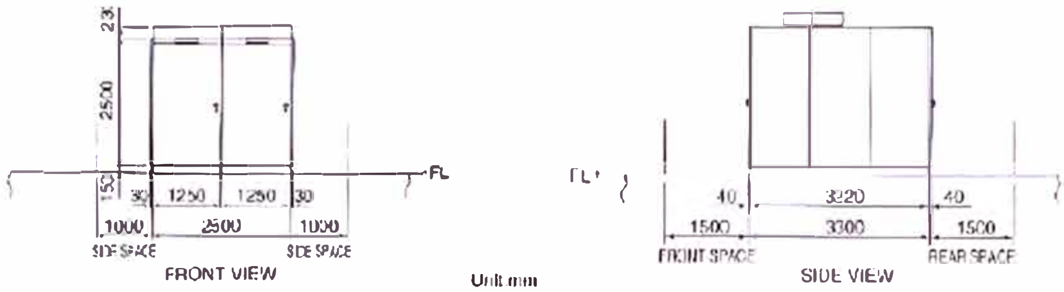


Fig.3.19 Dimensiones en Tipo Interior

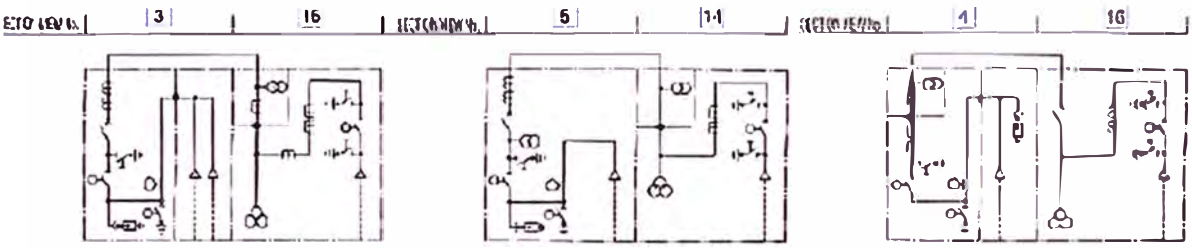


Fig.3.20 Arreglo de Componentes

(2) Una llegada doble, una unidad de medida y dos alimentadores

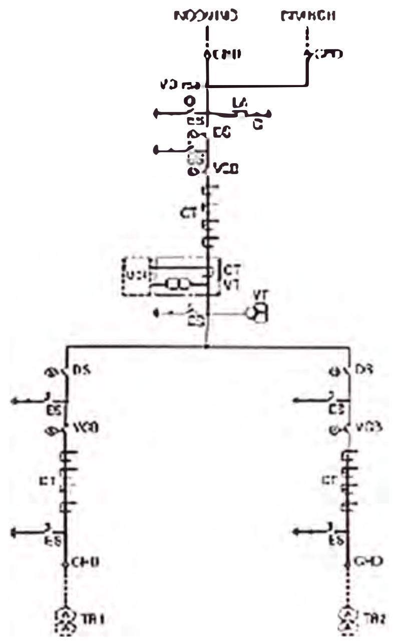


Fig. 3.21 Diagrama Unifilar Caso (2)

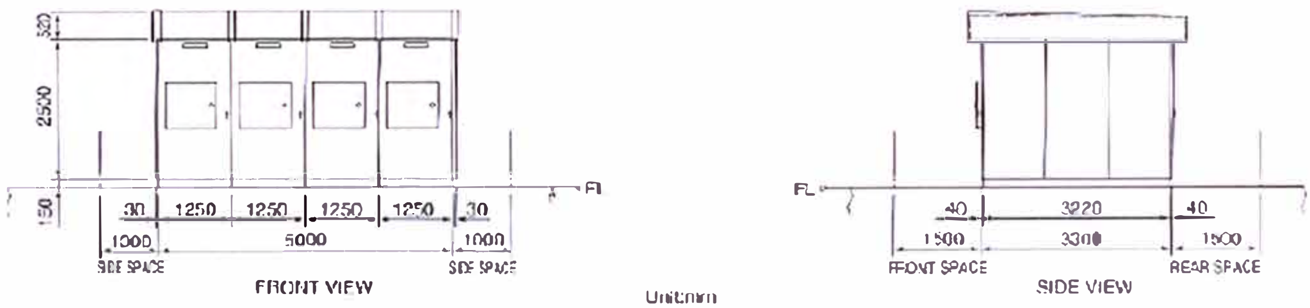


Fig. 3.22 Dimensiones Tipo Exterior

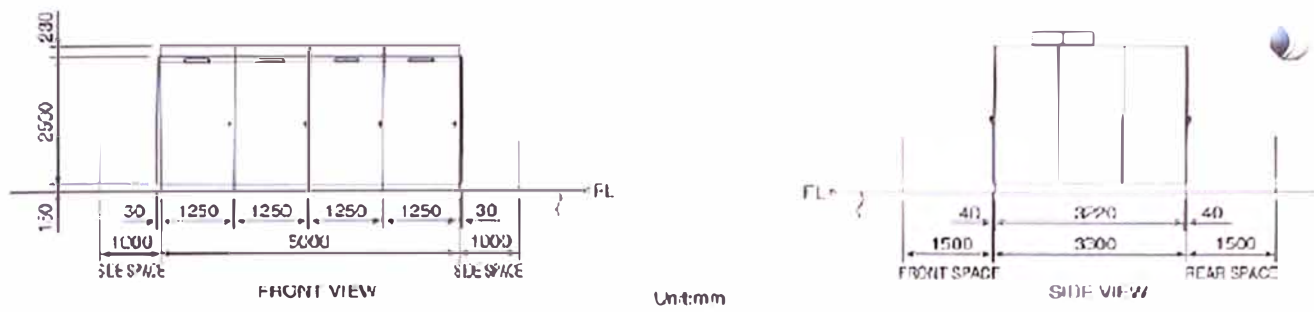


Fig. 3.23 Dimensiones Tipo Interior

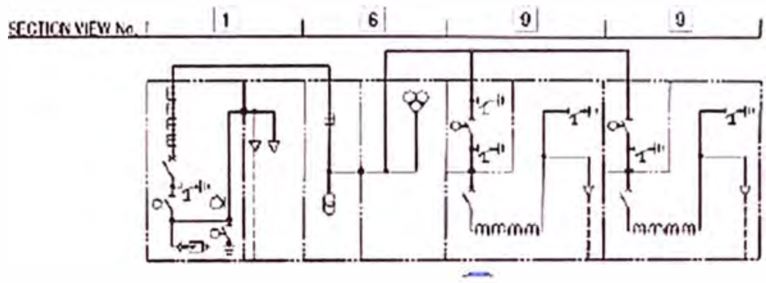


Fig. 3.24 Arreglo de Componentes

(3) Dos llegadas, Una unidad de medida y dos alimentadores.

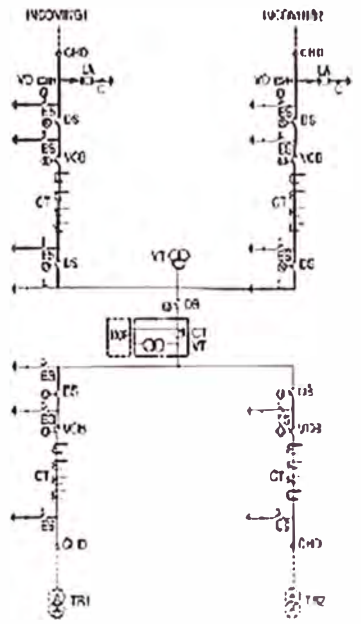


Fig. 3.25 Diagrama Unifilar

DIMENSIONES EN TIPO EXTERIOR

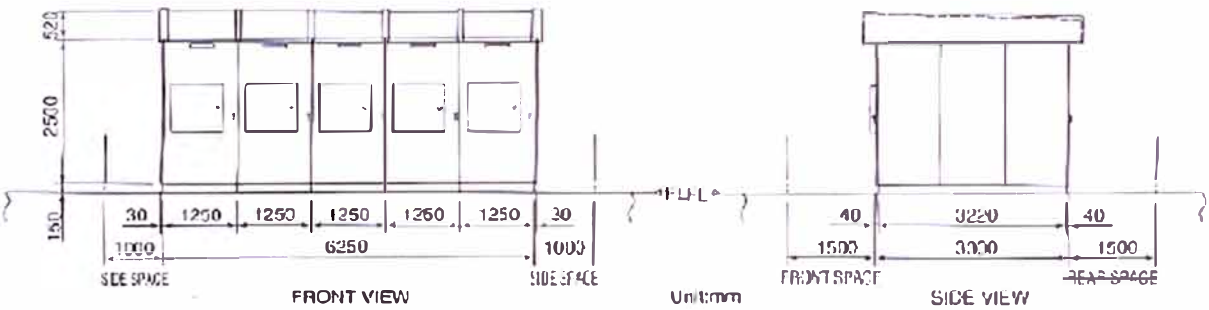


Fig. 3.26 Dimensiones en Tipo Exterior

DIMENSIONES EN TIPO INTERIOR

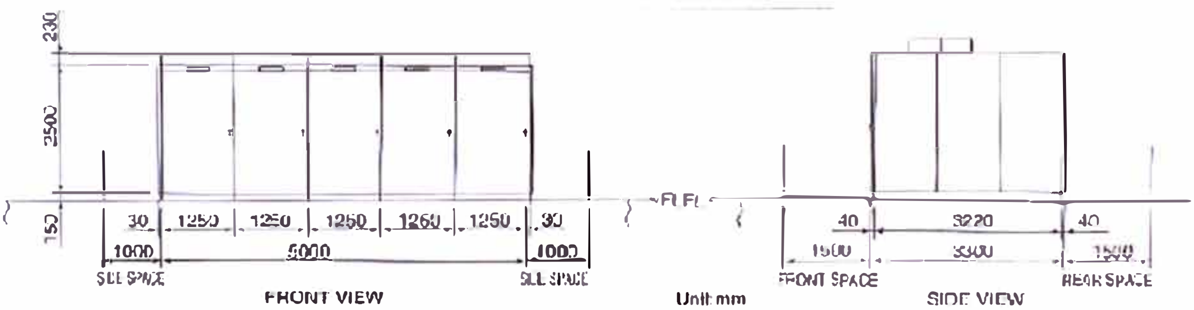


Fig. 3.27 Dimensiones en Tipo Interior

ARREGLO DE COMPONENTES

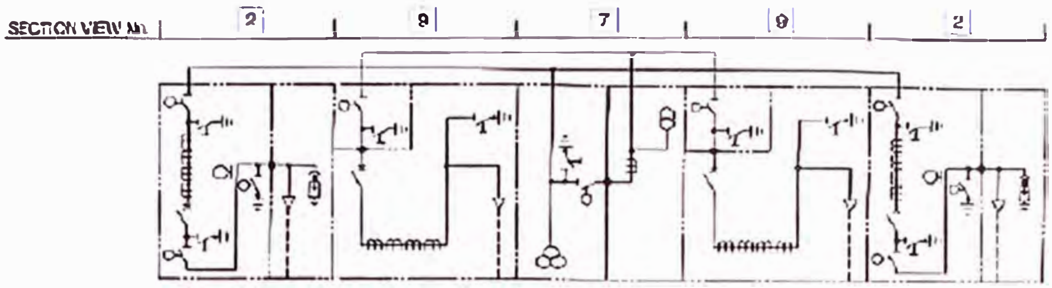


Fig. 3.28 Arreglo de Componentes

Esquema Unifilar

(3) Dos llegadas dobles, dos unidades de medida una barra de enlace y dos alimentadores

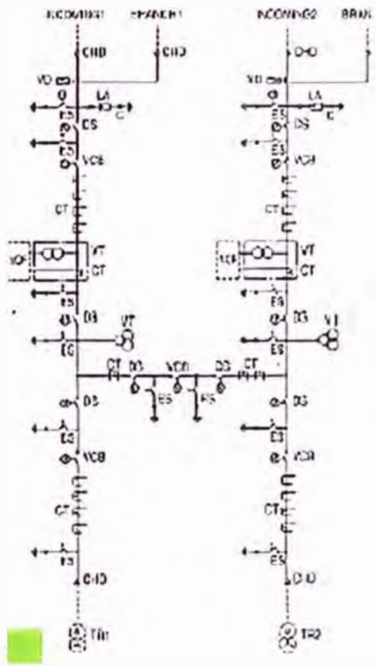


Fig. 3.29 Esquema Unifilar

DIMENSIONES EN TIPO EXTERIOR

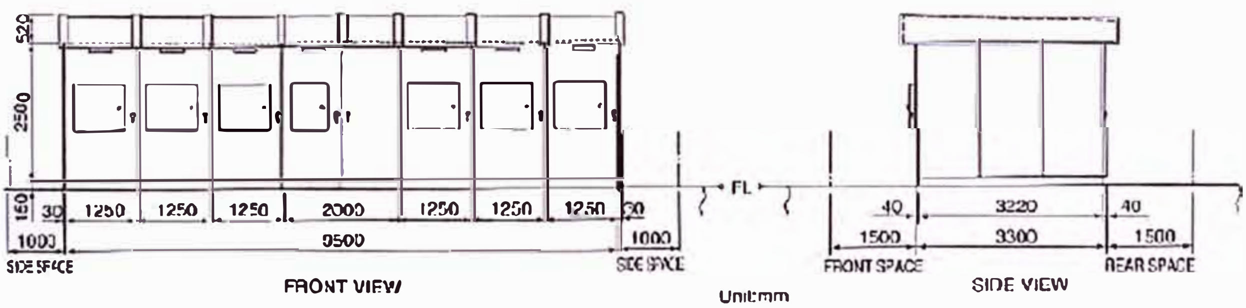


Fig. 3.30 Dimensiones en Tipo Exterior

DIMENSIONES EN TIPO INTERIOR

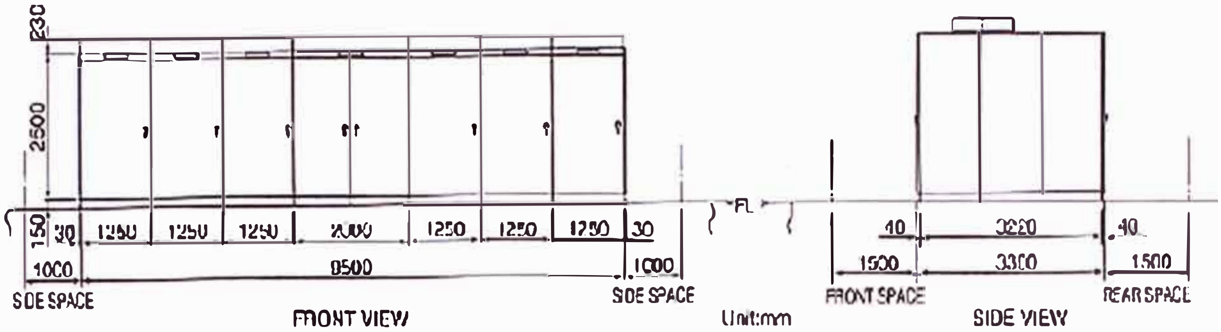


Fig. 3.31 Dimensiones en Tipo Interior

ARREGLO DE COMPONENTES

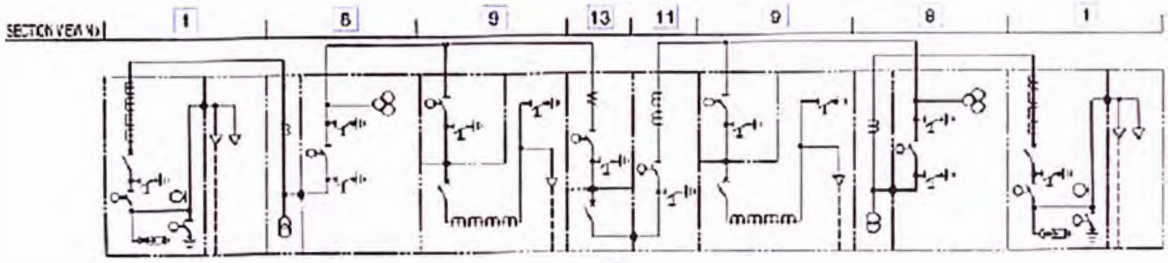
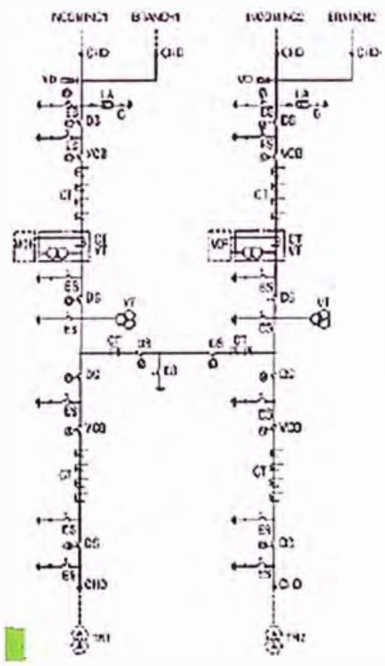


Fig. 3.32 Dimensiones en Tipo Interior

Esquema Unifilar

(3) Dos llegadas dobles, dos unidades de medida, una barra de enlace y dos alimentadores



DIMENSIONES EN TIPO EXTERIOR

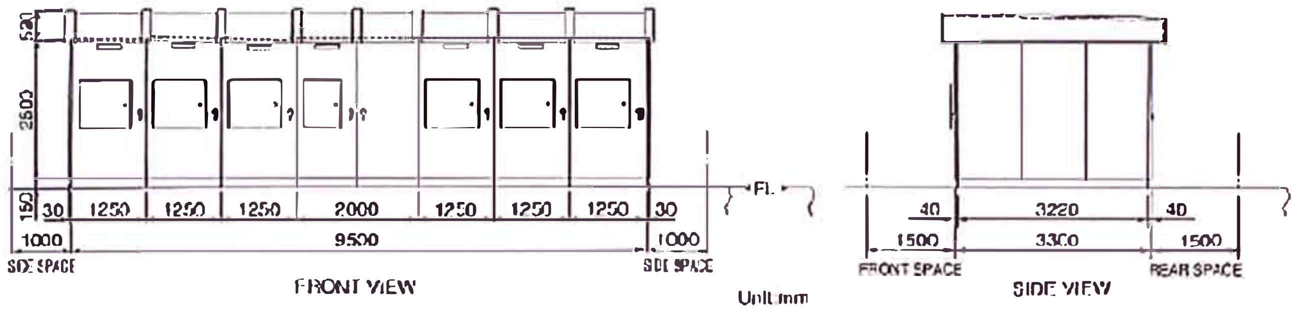


Fig. 3.33 Dimensiones en Tipo Exterior

DIMENSIONES EN TIPO INTERIOR

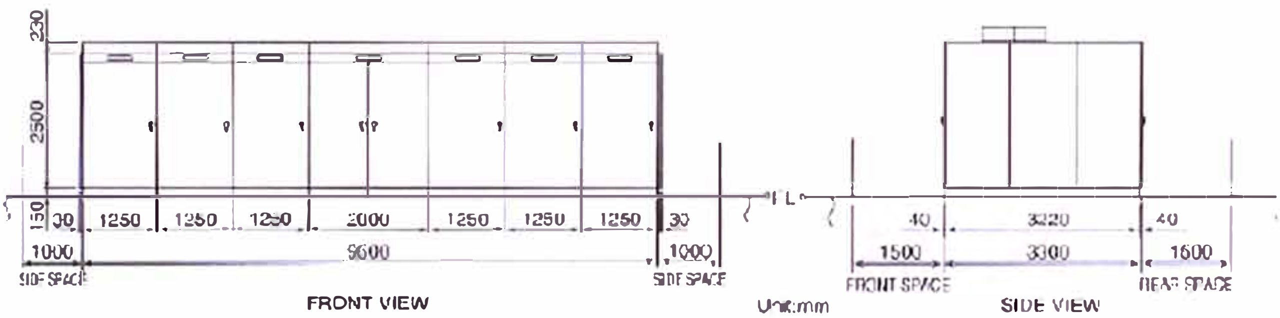


Fig. 3.34 Dimensiones en Tipo Interior

ARREGLO DE COMPONENTES

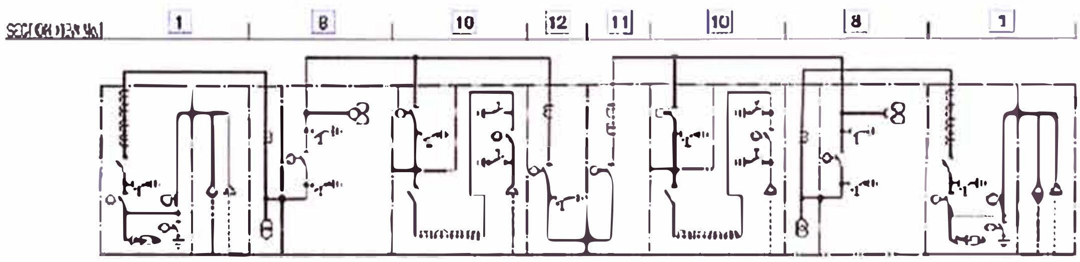


Fig. 3.35 Dimensiones en Tipo Interior

VISTAS EN CORTE

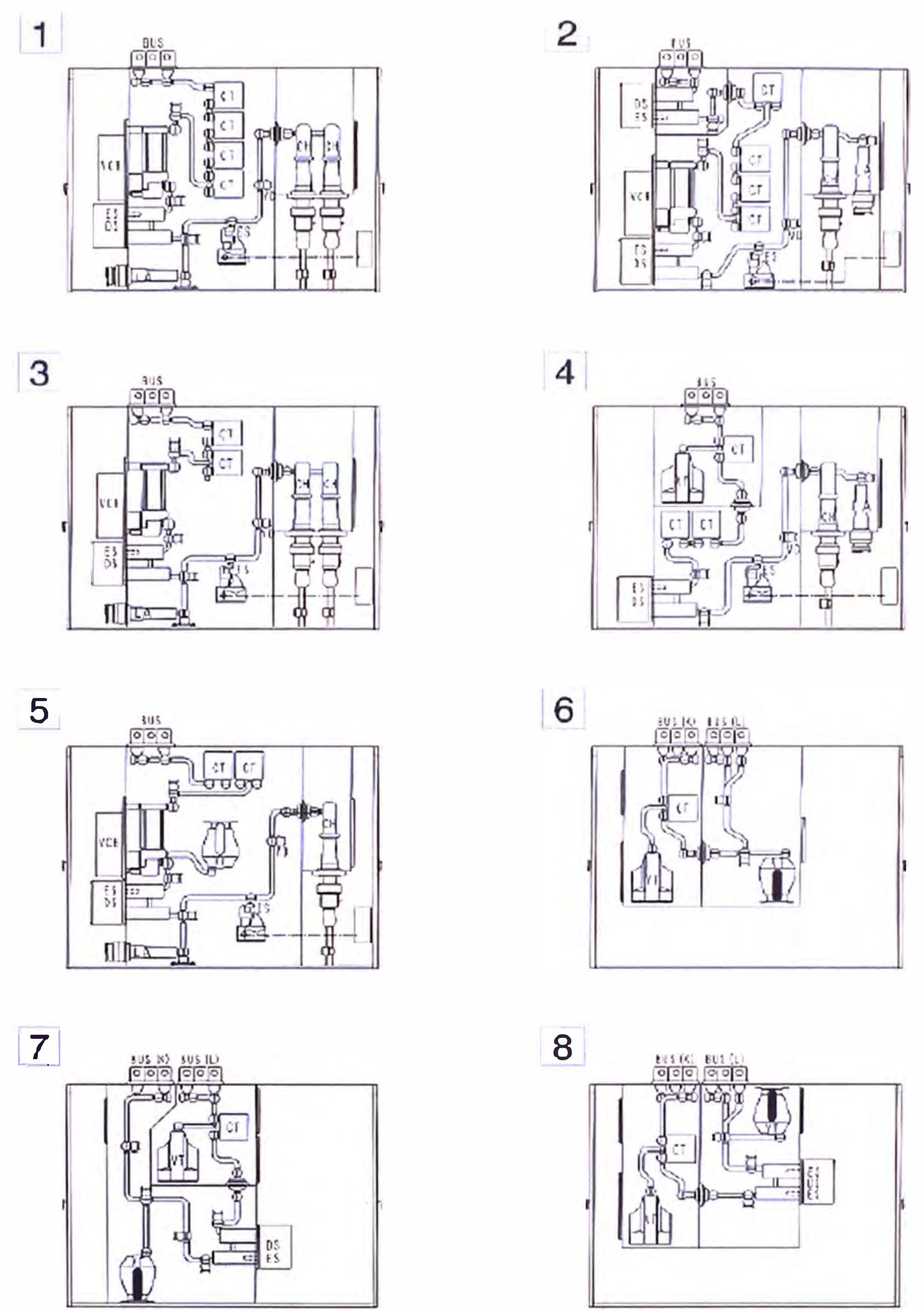


Fig. 3.36 Dimensiones en Tipo Interior

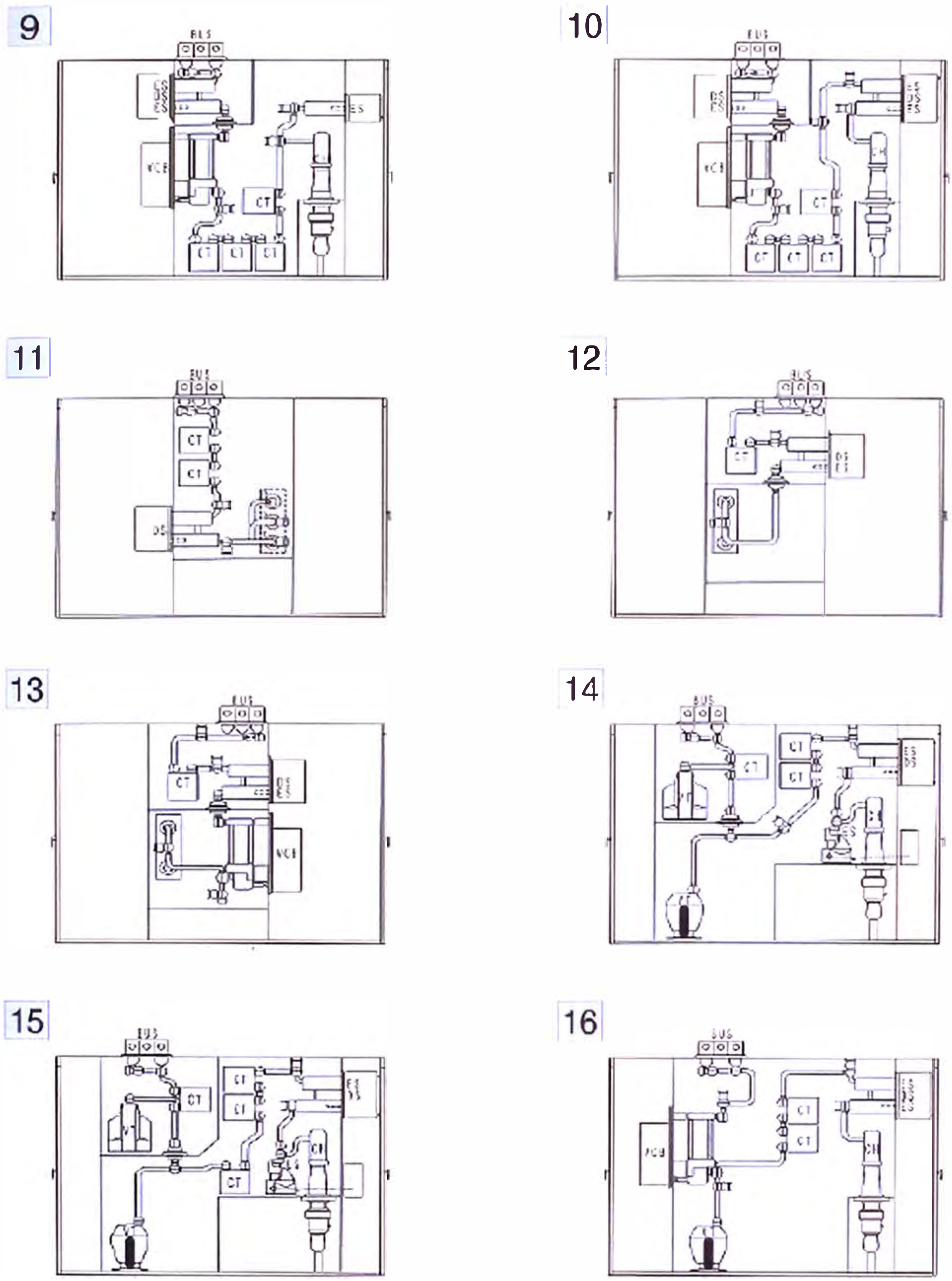


Fig. 3.37 Dimensiones en Tipo Interior

3.6 Impacto Ambiental

Entre las múltiples tareas que hoy enfrenta la industria eléctrica a nivel mundial, un tema prioritario es la preservación del medio ambiente. En este sentido, los fabricantes vienen trabajando en el desarrollo de nuevos equipos, no solamente técnicamente eficientes, sino también capaces de reducir de modo consistente el impacto que sobre el ambiente generan las nuevas instalaciones.

Desde este punto de vista, las celdas metálicas C-GIS en 60kV, se consideran afines con el medio ambiente, toda vez que no utilizan gas SF6 para extinguir el arco, tal como se aplica en la mayoría de interruptores de alta tensión. Sabido es que durante la interrupción del arco eléctrico, debido a las altas temperaturas que se generan, se produce la descomposición parcial del gas, quedando como residuo, otros gases y sustancias químicas contaminantes altamente nocivas para el ambiente.

Sobre este mismo tema, a partir de protocolo de Kyoto, en 1997, el gas SF6 fue listado entre los gases causantes del efecto invernadero, precisándose que el gas SF6 producía un efecto invernadero equivalente a 24,000 veces el ocasionado por el CO_2.

En concordancia con dicho protocolo, el empleo de gas SF6 como medio aislante ya no es más recomendable y la industria se ha volcado desde entonces a la búsqueda de soluciones que permitan reemplazar dicho gas, sin perjuicio de los beneficios ya obtenidos. Un paso importante es el observado en las nuevas soluciones en celdas de media tensión 24/36kV, mediante el empleo de aislamiento sólido (SIS), descartando el uso de gas SF6 y cumpliendo con los requerimientos medioambientales vigentes. El asilamiento SIS es una solución moldeada a partir del reciente desarrollo de la resina epóxica híbrida. La solución contempla que además de los interruptores, los seccionadores también empleen únicamente vacío y que los accionamientos a motor y resortes sean reemplazados por mandos modernos y eficientes, como los actuadores magnéticos.

Las celdas SIS para media tensión, tienen un menor volumen 60% y un menor peso 50%, que celdas equivalentes C-GIS.

Fig. 3.38 Celdas con aislamiento sólido

Factor 4.88 (SIS^{Note1}/$C\text{-}GIS^{Note2}$)

Note1) SIS: Solid insulated switchgear

Note2) C-GIS: Cubicle type gas insulated switchgear

Los esfuerzos desplegados por la industria, a partir de protocolo de Kyoto, para retirar de sus programas el empleo de gas SF6, han servido para evolucionar de modo notable en el diseño de nuevas soluciones para media y alta tensión.

Una solución particular C-GIS para 60kV, compatible con el medioambiente, ha sido puesta en el mercado. Se trata del C-DAIS, que consiste en celdas parecidas a las C-GIS, en las que se ha reemplazado el gas SF6, por aire seco a una presión de 0.5MPa. Se adjunta unas vistas y características de dicho sistema, considerado 100% amigable con el medio ambiente.

Tabla 3.8	Celda Aislada con Aire seco Presurizado 60kV

Características

No empleo de gas SF6

Celda aislada con Aire Seco a presión

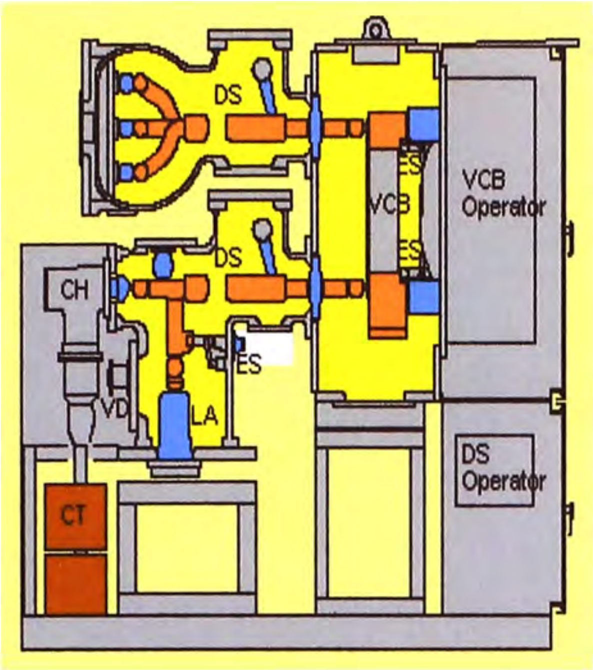
Alta confiabilidad

Fácil de mantener

Datos Técnicos

Tensión Nominal [kV]	72.5
Capacidad de ruptura [kA]	25
Corriente Nominal [A]	1250
Tipo de interruptor	VCB
Mando del interruptor	Resorte cargado por motor
Rangos de Presión del Aire seco	VCB 0.45MPa Otros 0.5MPa
Normas aplicables	ANSI/IEC

Configuración



L2'11" x W9'6" x H9'2"

[L2900 xW900 x H2800 (mm)]

Tabla 3.9 Botellas de Vacío

Rangos para Interruptores:

De 7.2kV a 145kV

De 630A a 3150A – 20kA a 50kA

Para Contactores:

7.2kV a 36kV

400A, 630A-3kA/4kA

Características:

Método de extinción simple

Construcción sencilla de alta calidad

No hay gases que evacuar

Diseño compacto

Tabla 3.10 Para Interruptores

Tensión nominal	Corriente nominal	Corriente de cortocircuito con componente DC de 30-40% mínimo y diámetro externo de la botella de vacío (mm)						
kV	A	12.5kA	16kA	20kA	25kA	31.5kA	40kA	50kA
12/15	630		M52QC (Ø65)	M41QC (Ø73)				
	800/1250				M51RC (Ø82)			
	1600/2000				M61RQC (Ø94)	M71SC (Ø94)	M81SC (Ø110)	
	2500/3150					M71TC (Ø110)	M81TC (Ø132)	MA131TC (Ø150)
17.5/24	630		M52QC* (Ø65)					
	800/1250				M102R (Ø94)			
	1600/2000				M102S (Ø94)			
	2500/3150					M132TC (Ø120)	M203TCB (Ø120)	
36/38	630	M83QC* (Ø65)	M93QC* (Ø94)					
	800/1250			M163RC* (Ø110)				
	1600/2000				M163SC (Ø120)			
	2500/3150					M203TCB* (Ø120)	M253TC* (Ø132)	
72.5	1250/2000						MA467SC* (Ø150)	
123	2000						M8301TX* (Ø190)	
145	2000						M10014TX*	

(Ø240)

CAPITULO IV

EJEMPLO COMPARATIVO

4.1 Objetivo

El objeto de este capítulo es ver, a través de un ejemplo, una aplicación práctica de una instalación C-GIS en 60kV. Incluyendo un análisis básico de las variables económicas y otras, que pueden incidir al momento de una toma de decisión, para saber si una instalación en 60kV debe construirse siguiendo una solución convencional o más bien se puede recomendar la implementación de una solución C-GIS, mediante celdas encapsuladas con interruptores en vacío.

La instalación en 60kV que se toma en este ejemplo se denomina “SE Textil Piura”, y corresponde a un cliente privado, la empresa Industria Textil Piura, que se dedica a la fabricación de hilados de algodón en la ciudad de Piura y cuya demanda se caracteriza por ser prácticamente plana a lo largo del año. Evidentemente, el trabajo que se plantea con esta subestación de ejemplo, no es aplicable para cualquier otro tipo de cliente o propietario, como podría ser en el caso de una empresa eléctrica distribuidora o de transmisión, cuyas decisiones pueden involucrar algunas otras variables, como por ejemplo el análisis de la confiabilidad del sistema o las potenciales multas y compensaciones a clientes en caso de fallas, propias de las normas o disposiciones regulatorias.

La SE Textil Piura, se construyó en Piura, en el año 1995, a la altura del km 3 ½ de la carretera Piura Sullana. Se alimenta en 60kV por medio de la línea de transmisión proveniente de la Subestación Piura Oeste en dirección a Sullana y cuenta con un transformador de 12MVA ONAF, con regulación bajo carga.

4.2 Proyecto

Del punto de vista eléctrico, la SE Textil Piura tiene un esquema π (phi), y está compuesta por una simple barra en 60kV, una bahía para la llegada procedente de la

Subestación Piura Oeste, una bahía de salida en dirección a Sullana y una tercera bahía para alimentar el transformador de potencia de 12MVA de la propia subestación. La instalación fue diseñada de tipo interior, debido al polvo y la contaminación presente en la zona.

Para el presente trabajo hemos asumido que, a manera de ejemplo, se nos encarga tomar la decisión del equipamiento y construcción de dicha subestación en la fecha. Se tiene para elegir entre una solución en interior del tipo convencional, con interruptores en SF6, y otra solución moderna tipo C-GIS, con interruptores en vacío. La tarea es, entonces, evaluar mediante un análisis comparativo, cual de las alternativas disponibles es la más conveniente. Para ello tendremos que ponderar todas las variables comprometidas en el proyecto y en su posterior funcionamiento. Mediante dicha evaluación podremos saber si se debe recomendar la subestación de diseño en interior con equipo convencional o las celdas encapsuladas C-GIS en 60kV.

Una tercera posibilidad se podría añadir al presente análisis, si asumimos, por ejemplo, que la subestación ya existe, que tiene 20 años de antigüedad, que el equipamiento es de tipo convencional a la intemperie y que la instalación requiere de una pronta rehabilitación para poder seguir operando en forma satisfactoria. En consecuencia, el propietario tendría las siguientes alternativas:

a) Manteniendo la instalación que tiene, llevar a cabo una repotenciación de la instalación.
b) Construyendo una nueva subestación empleando tecnología convencional en SF6.
c) Construyendo una nueva subestación empleando tecnología de celdas C-GIS, con interruptores de vacío.

Para un primer análisis comparativo se necesitará conocer, independientemente del costo de la repotenciación para la primera alternativa, el costo de la ejecución del proyecto y que considere como mínimo lo siguiente:

1. Costo del terreno y de la obra civil
2. Costo del equipamiento
3. Costo de la instalación
4. Costo del mantenimiento a 30 años

El costo de la ingeniería no se tomará en consideración, debido a que se supone será el mismo para cualquiera de las dos soluciones con equipamiento nuevo.

En principio, puede considerarse que ambas instalaciones son técnicamente equivalentes, y un cuadro comparativo económico nos mostrará, de desde ese punto de vista, cual de las dos alternativas es la más conveniente. Obviamente para una empresa de transmisión o para una empresa distribuidora de electricidad, podría ser necesario trabajar en un análisis más exhaustivo, que involucre otros aspectos igualmente importantes, tales como la rapidez con que se puede efectuar el montaje, la robustez del conjunto en caso de sismos, la sencillez para el mantenimiento, la seguridad del personal contra accidentes, la confiabilidad en la operación, la garantía por su previo ensayo en fabrica, la capacidad de soportar inundaciones, etc.

También se pueden dar situaciones en las cuales, por las condiciones de operación o de la ubicación de la instalación, no cabe hacer mayores comparaciones y el empleo de las celdas C-GIS resulta ser una solución única. Por ejemplo si se trata de un edificio dentro de la ciudad, en el que se tiene una subestación convencional de tipo interior y se requiere renovar equipos o ampliar el número de celdas y no se dispone de más espacio, ni se tiene un terreno libre próximo.

Igualmente pude ser una solución indiscutible si se aplica en zona de sismos o también es el caso en algunos países del Asia, incluyendo el Japón, cuyas instalaciones en 60kV próximas al mar consideran las celdas C-GIS como solución obligatoria, frente a posibilidad de maremotos o tsunamis.

Se presentan los esquemas unificares correspondientes al proyecto de subestación SE Textil Piura:

1.- Diagrama Unifilar en 60kV, Existente
Correspondiente al equipamiento convencional en 60kV para uso interior.

2.- Diagrama unifilar 60kV, Modificado
Correspondiente a la solución mediante el empleo de celdas blindadas en 60kV, Tipo C-GIS.

Fig. 4.1 Diagrama Unifilar en 60kV, Existente

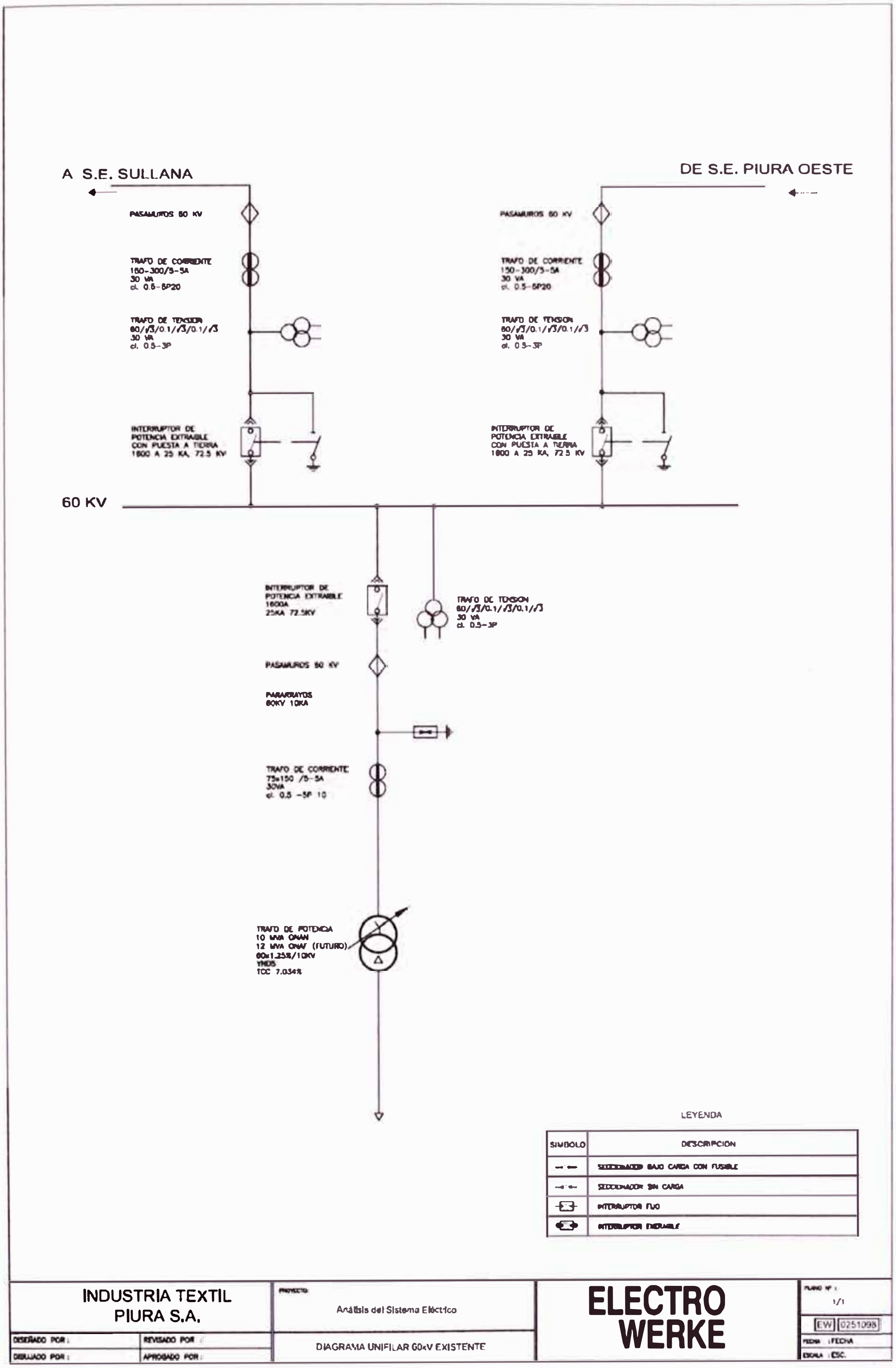
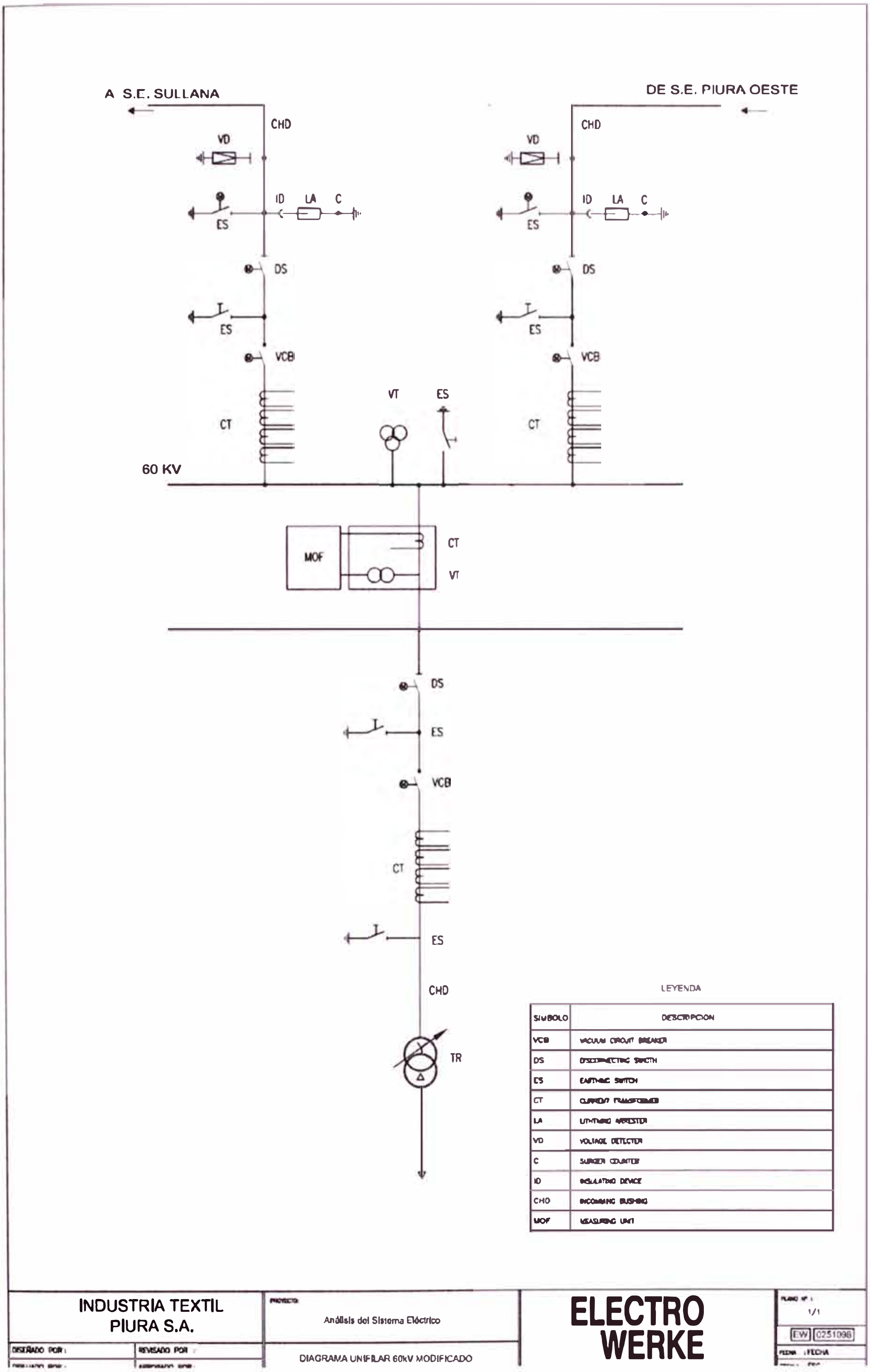


Fig. 4.2 Diagrama unifilar 60kV, Modificado



4.3 Terreno y Obra civil

La obra civil de la subestación Industria Textil Piura, solo en la parte correspondiente al equipo de maniobra en 60kV, consiste en un edificio de concreto armado, que ocupa un terreno de 9.50 de largo por 7.50m de ancho y 6.50m de altura. El área de terreno construido solo para los equipos en 60kV es de 71.25 m².

En la alternativa de instalación con celdas C-GIS, se necesitaría un terreno de 5.00m de largo por 3.30m de ancho. El área de terreno en este caso es de solo 16.50 m², menos de la cuarta parte del terreno usado por la solución convencional.

Si comparamos la obra civil de ambas alternativas encontramos diferencias notables. En el caso de la subestación C-GIS la obra civil se reduce a una plataforma sobre la cual irán montadas las celdas, mientras que en la subestación interior tenemos además del casco, los muros entre bahías, los cercos de protección interior, la iluminación, las fundaciones para el anclaje de equipos, las puertas y las ventanas.

Debido a que la subestación al interior se construyó en un terreno dentro de los linderos de la fábrica, el costo del terreno se asume como uno adquirido en el mercado para fines industriales. Para efectos de comparación, se considera que el terreno se limita al área empleada por la instalación, tanto para la subestación en interior como para la subestación C-GIS. Es decir, no se toma en cuenta las áreas de acceso, las pistas, ni las veredas.

Asimismo, se considera que la malla de tierra profunda tiene dimensiones similares para ambas soluciones, al igual que las canaletas y ductos en el piso, por lo tanto estos detalles, dentro de la obra civil, no se toman en cuenta al momento de hacer la comparación.

4.4 Equipamiento

La subestación SE Textil Piura, cuenta con tres bahías en 60kV, cada una conteniendo el siguiente equipamiento:

Un interruptor de potencia en SF6, extraíble
Un juego de transformadores de corriente

Un juego de transformadores de tensión

La instalación cuenta además con los siguientes equipos, apropiados para instalación al interior en 60kV, comunes para todas las bahías:

Un juego de barras colectoras en tubo de cobre
Un conjunto de aisladores soporte
Un conjunto de conectores y elementos de ferretería
Dos juegos de pasamuros exterior-interior
Un juego de tableros de protección y control
Un juego de cables de baja tensión para el control

La solución alternativa mediante celdas C-GIS, comprende tres celdas encapsuladas para montaje al exterior, todas equipadas de modo similar con interruptor en vacío, transformadores de medida y protección, ingreso superior mediante pasamuros tipo intemperie en 60kV, con excepción de la celda central provista de un ducto de barras aisladas, para conectarse directamente con el transformador de potencia. Cada celda lleva además incorporado, en su compartimiento de baja tensión, un juego de relés de protección multifunción, contadores de energía, panel mímico y anunciador de alarmas.

4.5 Instalación

La instalación del equipamiento en 60kV de la subestación de Industria Textil Piura, tomó 2 ½ meses. Mientras que la instalación mediante celdas C-GIS, se estima que podría tomar 4 semanas.

A diferencia de las celdas C-GIS, que llegan a la obra previamente ensambladas y probadas de fábrica, y que solo requieren ser montadas en el sitio y conectadas, el equipamiento de la subestación en interior requiere, además de los ensayos finales como conjunto, de un ensamble complejo y prolongado. Normalmente la instalación empezará por el ensamble del sistema de barras en 60kV, para luego continuar con el resto de los equipos, interruptores, seccionadores, trasformadores, etc., terminando con la instalación de la parte de control y protección en baja tensión.

El costo de la instalación para ambos casos se indica en el cuadro comparativo.

4.6 Mantenimiento

Debido a que la instalación de 60kV de la subestación Textil Piura es en interior, los equipos no están expuestos al medio ambiente y, por lo tanto, solo necesitarán de un mantenimiento mínimo.

Del mismo modo, una instalación equivalente considerando celdas C-GIS, también necesitaría solo de un mantenimiento mínimo. En todo caso, se podría asumir que el costo del mantenimiento para ambas instalaciones resulta equivalente.

En el caso de que la instalación de 60kV de la subestación de Industria Textil Piura fuese convencional, a la intemperie, los requerimientos de mantenimiento serian mucho mayores. La sola limpieza de los equipos, principalmente de los aisladores, obliga a parar normalmente dos veces por año y en lugares muy contaminados y sin lluvias hasta cuatro veces por año.

Las empresas de electricidad conocen bien que, un alto número de paradas o interrupciones del servicio por motivo de mantenimiento, puede llegar a ser un serio problema. Sabido es que la norma vigente de la "Calidad de la Energía" es sumamente exigente en ese aspecto y, en casos extremos, contempla la aplicación de elevadas multas por su no cumplimiento.

En el caso especifico de cargas importantes, lo ideal es que las interrupciones por mantenimiento sean las mínimas posibles y programadas con la debida antelación. Siguiendo tal criterio la subestación en 60kV de Industria Textil Piura, fue construida de tipo interior. La fábrica funciona 24 horas diarias a lo largo del año, parando una sola vez en diciembre para efectuar el mantenimiento integral de la planta. Debido a lo complejo de dicha fabrica, cualquier corte de energía no programado puede ocasionar graves daños en la producción, no solamente por lo que se deja de fabricar, sino por el daño irreparable de lo ya producido.

En base a lo anterior, es importante notar que al momento de evaluar el costo de mantenimiento para una subestación se debe incluir, además del costo por el mantenimiento preventivo y correctivo durante la vida útil de la instalación, el costo adicional o lucro cesante ocasionado por la energía que se dejo de vender durante el mantenimiento. Tratándose de un usuario como en el caso de Industria Textil Piura, el costo adicional correspondería a lo dejado de producir, como consecuencia de los cortes por mantenimiento.

4.7 Costos

Un análisis comparativo implica conocer el costo de las alternativas que se quiere evaluar. En este caso se trata de comparar una instalación con equipo convencional en interior y la otra equivalente a partir de celdas C-GIS. Cabe precisar que la comparación se limita al nivel de 60kV, por lo tanto no se toman en cuenta costos tales como el del transformador de potencia, del equipamiento auxiliar, ni del resto de la instalación, ya que estos se repiten para ambas alternativas.

Para continuar con el ejercicio planteado al inicio de este capitulo, con respecto a repotenciar una subestación existente, como tercera opción. Se propone reemplazar por equipo nuevo todo el patio de llaves, con lo cual se tendría una figura comparativa, aunque solo a nivel económico.

El cuadro comparativo reúne los costos de las principales variables que podemos cuantificar, como son:

- Costo del terreno
- Costo de la obra civil
- Costo del equipamiento
- Costo de la instalación

El terreno utilizado por la subestación interior, solo para alojar los equipos en 60kV, es de 71.25 m². El precio del terreno de la fábrica se ha estimado en US$ 120.00 / m², en consecuencia el costo del terreno de la solución en interior resulta 71.25 x 120.00, es decir US$ 8,550.00. De modo equivalente, el costo del terreno para la solución mediante celdas C-GIS resulta 16.50 x 120.00, es decir US$ 1,980.00.

Para el caso de la subestación convencional con equipamiento a la intemperie estamos considerando un terreno equivalente a seis veces el área ocupada por el edificio para la instalación en interior. Todos los demás datos correspondientes a esta alternativa, tales como el costo de la obra civil, el equipamiento y la instalación son valores asumidos y corresponden a los precios del mercado.

La obra civil en la solución convencional corresponde a un edificio de 9.50 de largo por 7.50m de ancho y 6.50m de altura. Su costo es fuertemente influenciado por las características del terreno y a las exigencias de robustez, propias de una subestación. La obra comprende además la malla de tierra y los cimientos.

Debido a que el costo del mantenimiento durante la vida útil ha sido considerado equivalente en ambas alternativas, el costo de dicho rubro no ha sido tomado en cuenta en el cuadro comparativo.

En cuanto al equipamiento se aprecia que el costo de ambas soluciones tienen un nivel cercano, sin embargo se puede decir que normalmente el costo del equipamiento de una instalación convencional siempre será mucho menor que el de la solución encapsulada C-GIS equivalente.

En el cuadro comparativo adjunto, se encuentra una diferencia notable de costo de instalación entre las soluciones b y c. Se entiende que este rubro comprende el montaje, las pruebas y la puesta en marcha del conjunto. Como dato importante se puede mencionar que el plazo de ejecución de la instalación de la subestación al interior requiere de 2½ meses. Mientras que la instalación mediante celdas C-GIS, solo necesita de 1 mes. Esta importante reducción del tiempo de ejecución, puede también ser motivo de una valoración específica dependiendo de la urgencia del proyecto,

Tabla 4.1 Cuadro Económico
Instalaciones Alternativas en 60kV

ITEM	COMPONENTE	Equipamiento Repotenciado (a)	S.E. Interior con Interruptor en SF6 (b)	S.E. con Celdas Tipo C-GIS (c)
1.1	Terreno	51,300	8,550	1,980
1.2	Obra civil	20,000	118,100	13,500
1.3	Equipamiento	300,000	566,500	696,000
1.4	Instalación	25,000	43,150	15,900
	COSTO TOTAL	**US$ 396,300**	**US$ 736,300**	**US$ 727,380**

De los resultados mostrados en la Tabla 4.1, se podría concluir que la opción más conveniente es la de repotenciar. También se puede ver que entre las dos soluciones completas con equipo nuevo, la solución más conveniente del punto de vista económico es el sistema C-GIS.

Con el fin de poder utilizar los resultados económicos en una evaluación final necesitamos construir una tabla de puntuación económica, en la cuál asignamos un puntaje máximo de 50 puntos a la alternativa con menor costo y puntajes inversamente proporcionales para las demás.

Tabla 4.2 Puntaje Económico
Instalaciones Alternativas en 60kV

ITEM	ALTERNATIVA	Equipamiento Repotenciado (a)	S.E. Interior con Interruptor en SF6 (b)	S.E. con Celdas Tipo C-GIS (c)
	PUNTAJE	50	26.90	27.24

4.8 Confiabilidad

Hasta aquí se han comparado las alternativas, mencionando las ventajas y desventajas de una y otra solución. Cabe señalar que el Cuadro Económico Comparativo es válido en la medida que todas las soluciones posean el mismo grado particular de confiabilidad. De otro modo, y al igual que se pondera en las licitaciones públicas, el precio y las características técnicas, en este caso tendríamos que establecer una ponderación diferenciada para el resultado económico y para la confiabilidad.

Normalmente la determinación del grado de confiabilidad requiere de una evaluación de condiciones anticipadas de operación y la continuidad del servicio requerida por la carga a la que tenga que servir. Para el cálculo de la confiabilidad en sistemas de transmisión, se recurre a métodos estadísticos, datos históricos y modelos matemáticos, haciendo de este tema toda una compleja especialidad.

Sin embargo, para nuestro caso, hemos recurrido a los conceptos de confiabilidad y mediante el uso los factores universales, anotados en el Capítulo II, podemos construir nuestro cuadro de confiabilidad para este proyecto, definiendo en primer lugar una puntuación porcentual para los cinco factores, con relación al equipamiento, tales que establezcan la puntuación de referencia para el equipamiento ideal y que se anota en la primera columna con el máximo puntaje de confiabilidad.

Los valores asignados son todos estimados y considerados como criterios propuestos por un comité a cargo de este trabajo, compuesto por profesionales, tanto del lado del cliente como del consultor a cargo del proyecto.

Tabla 4.3 Confiabilidad de la Instalación

Factor	Confiabilidad de la Instalación %			
	Instalación Ideal	**Equipamiento Repotenciado**	**SE Interior con Interruptor SF6**	**SE con Celdas tipo C-GIS**
Mediciones o pruebas	20	7	20	20
Carga de trabajo	25	15	25	25
Edad	20	5	20	20
Apariencia física	20	8	15	18
Medio ambiente	15	5	10	14
Totales	100	40	90	97

A partir de la información que se puede recoger del cuadro anterior, encontramos que la puntuación máxima corresponde al sistema de celdas encapsuladas C-GIS provistas con interruptor en vacío. Sin embargo, para integrar estos resultados con los económicos, necesitamos construir una tabla de puntajes por confiabilidad, en la cuál se asigna un puntaje de 50 puntos a la alternativa con mayor mérito por confiabilidad y puntajes directamente proporcionales para el resto de las alternativas.

Tabla 4.4 Puntaje por Confiabilidad

Alternativa	Instalación Ideal	Equipamiento Repotenciado	SE Interior con Interruptor SF6	SE con Celdas tipo C-GIS
Puntaje	50	20.6	46.4	50

Tomando los puntajes indicados en las Tablas 4.2 y 4.4, correspondientes a la evaluación económica y de confiabilidad, se obtiene un cuadro comparativo final, en el cual ambas evaluaciones tienen un peso máximo de 50 puntos. El puntaje máximo en este cuadro es de 100 puntos.

Tabla 4.5 Cuadro comparativo Final

Puntaje	Alternativa		
	Equipamiento Repotenciado	SE Interior con Interruptor en SF6	SE con Celdas tipo C-GIS
Económico	50	26.9	27.2
Confiabilidad	20.6	46.4	50
Totales	**70.6**	**73.3**	**77.2**

Se puede apreciar en este cuadro final que la recomendación será por utilizar la alternativa correspondiente al sistema con Celdas C-GIS, a la que le correspondió el puntaje total más alto.

CONCLUSIONES

El objeto del presente trabajo ha sido dar a conocer una nueva solución técnica para instalaciones en 60kV, denominada celdas C-GIS, y establece algunas pautas generales para comparar dicha solución innovadora frente a instalaciones convencionales.

A continuación, siguen las conclusiones del presente trabajo:

1. Una nueva tecnología de celdas en subestaciones de 60kV

En la actualidad, a nivel nacional, las subestaciones de 60kV utilizan equipos convencionales, con interruptores en SF6 y aislamiento en aire. En el futuro, tratándose de nuevos proyectos, podremos analizar el empleo de la nueva tecnología de celdas C-GIS que, dependiendo de la aplicación, puede representar indudables ventajas sobre las instalaciones convencionales.

La nueva tecnología no solo aporta el uso del nuevo interruptor de vacío en alta tensión. Se trata de una propuesta mucho más amplia e integral, es un solución completa, compuesta por celdas modulares equipadas con interruptores de alta tensión en vacío y que, al igual que en media tensión, solo requieren de un trabajo menor en el sitio para completar su instalación.

2. Mejor empleo del terreno y de la obra civil

Las subestaciones de tipo convencional, a la intemperie, suelen ubicarse fuera de las ciudades y en pocas ocasiones dentro de la misma ciudad, en cuyo caso, la extensión del terreno y su costo, suelen convertirse en un serio problema. Precisamente en estos casos, los sistemas GIS son una solución eficaz, debido al mínimo terreno que requieren. En el presente trabajo hemos visto que las celdas C-GIS tienen las mismas ventajas que los sistemas GIS, con la ventaja adicional de tener un menor peso, debido a que emplean interruptores en vacío más livianos. Por otro lado, la solución C-GIS es ideal para reemplazar subestaciones de 60kV de tipo interior, ya que solo necesitan menos del 40% o del área usada por los sistemas convencionales. Finalmente, las celdas C-GIS, además de ser una solución compacta con mínimas necesidades de terreno, no necesitan de un edificio especial y pueden ser montadas a la intemperie, en cuyo caso pueden reducir aun más el costo del proyecto.

3. Solución integral económica

Los equipos convencionales de alta tensión con aislamiento en aire son, sin duda, los equipos más sencillos y de menor costo en el mercado, sin embargo en el presente trabajo se muestra que, desde el punto de vista integral, una instalación con tales equipos, no es necesariamente la solución más económica. Por el contrario, las soluciones empleando celdas C-GIS, como se demuestra en el análisis comparativo, pueden tener un mayor costo inicial como equipo, pero ser al final la mejor solución económica como conjunto. Por esta razón, al evaluar una solución, es preciso que el criterio sea integral y que no se limite al costo de los equipos, sobre todo tratándose de nueva tecnología, cuyo eventual mayor costo inicial puede ser compensado ampliamente gracias a sus ventajas.

4. Instalación más sencilla, rápida y de menor costo

Una de las ventajas más importantes de las soluciones con celdas C-GIS sobre las subestaciones con equipos convencionales, es la sencillez de su instalación. Ello, debido a que las celdas vienen completamente ensambladas y probadas de fábrica, lo cual redunda en una rápida ejecución del montaje y en un menor costo para el proyecto.

Adicionalmente, con las celdas C-GIS, hay un conjunto de pasos que se simplifican, tales como la ingeniería que es desarrollada por el fabricante de las celdas, la procura que se reduce a un solo proveedor, el menor riesgo durante el transporte por ser uno solo, el menor riesgo durante un eventual almacenaje, el nulo riesgo de arribo de equipamiento incompleto a obra, el bajo riesgo durante el manipuleo en la etapa de montaje y, finalmente, el mínimo de personal especializado para efectuar el montaje.

5. Riesgo Operacional

Independientemente de todas las ventajas antes anotadas hay una particularmente importante y que no se ha tocado aún. Con el nuevo diseño de las celdas C-GIS se aborda el manejo de la alta tensión, con procedimientos considerablemente seguros, que hasta hoy solo fueron de uso exclusivo para la media tensión. En consecuencia, los riesgos para el personal como para la propia instalación pueden considerarse mínimos. Esta particularidad de la solución C-GIS constituye una enorme ventaja en la operación de una subestación. La seguridad de una instalación C-GIS, en el caso de una empresa de electricidad, podría contribuir a reducir los costos no solo de los seguros involucrados, sino también a elevar considerablemente la confiabilidad en el sistema porque garantiza una mejor continuidad en el servicio, reduciendo el riesgo potencial de fallas, y de eventuales multas o compensaciones, de acuerdo a las normas de calidad del servicio.

6. El mantenimiento, una nueva perspectiva

En el pasado, al planificar o proyectar una subestación, el mantenimiento solo se considerada como un aspecto complementario y más bien correspondiente a la operación futura del sistema. Hoy, en cambio, es indispensable que se conozca el impacto que tendrá el mantenimiento en el costo del proyecto. Un equipo que requiere frecuentes paradas para cumplir con los programas de mantenimiento, tendrá implícitamente un mayor costo que aquel que requiera solo de un mínimo mantenimiento. Costo que no solo corresponde a las tareas de mantenimiento, sino también a los que se generan como consecuencia de las interrupciones o paradas, tales como energía dejada de vender o las perdidas de producción por fabricas o instalaciones detenidas. En este sentido los sistemas C-GIS se caracterizan por presentar una necesidad de mantenimiento mínima, no solo espaciada sino además de corta duración.

7. Impacto ambiental

En principio las celdas C-GIS, debido a que usan interruptores de vacío, son una solución no contaminante. No emplean gas SF_6 en la interrupción, sino únicamente como medio aislante. Sin embargo, en consideración a lo dispuesto en el protocolo de Kyoto, y debido a que el gas SF_6 ha sido listado como causante del efecto invernadero, los fabricantes están trabajando en nuevas tecnologías, con miras a reemplazar el uso del gas SF_6.

Al respecto, los nuevos desarrollos consideran seriamente el impacto ambiental. Por ejemplo, ya existe un nuevo diseño de celdas en 60kV, C-DAIS, las cuales emplearán aire seco a presión en lugar del gas SF_6, y cuyo costo se sabe que será mayor al de las C-GIS actualmente en uso. Es evidente que en el futuro, para que podamos evaluar apropiadamente dichos equipos, se necesitará establecer nuevos criterios de comparación, adecuados para compensar su eventual mayor costo frente a la ventaja de contar con soluciones modernas que protejan el entorno y el medio ambiente.

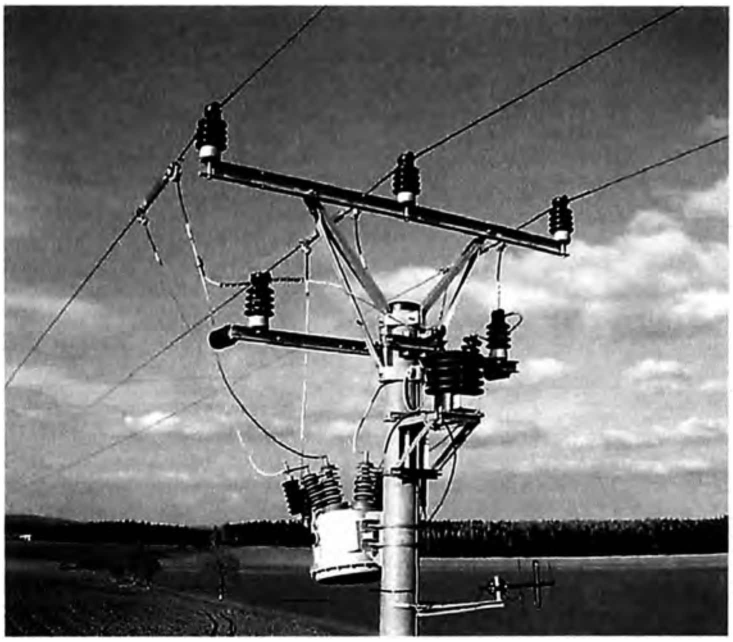
ANEXOS

ANEXO A

APLICACIÓN DE INTERRUPTORES DE VACÍO EN RECLOSER MT-W&BOURNE

Outdoor circuit breaker
GVR Recloser
Whipp & Bourne Switchgear

rated voltage 15, 27 and 38 kV
rated current 630 A



D R I B O

B R N O

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Outdoor circuit breakers GVR Recloser

GVR switchgear brings the reliability of modern materials and technology to overhead distribution networks

The reliability of a system is achieved through:

- a new, patented, single coil magnetic actuator mechanism which allows the GVR to operate independently of the HV supply and to be tested in an ordinary workshop;
- environmentally friendly vacuum interruption produces no by-products;
- the lightweight aluminium tank makes the GVR easier to transport and install;
- the EPDM rubber bushings are resistant to damage from vandalism or mishandling;
- by extensive use of insulated mouldings, in particular the bushings, the total number of parts has been reduced by a factor of x 20 and the number of moving parts by x 50.

Environmental design

The award-winning GVR gas-filled vacuum recloser combines the high reliability of vacuum interruption with the controlled environment and high dielectric strength of SF_6, in a compact, maintenance-free unit. Since SF_6 is only used as insulation, there is no health hazard from toxic by-products of arcing. Electrical life is well in excess of ANSI and IEC requirements.

The magnetic actuator provides consistent performance and a dramatic reduction in the number of moving parts. Materials and finishes have been carefully chosen for reliability – from EPDM bushings, tested for tracking and erosion to IEC 1109, in salt fog and other environments, to the neodymium iron boron permanent magnets used in the mechanism.

Application

The GVR can be pole mounted or substation mounted and can operate as a stand-alone recloser without the need for an additional auxiliary supply, or it can be integrated into the most advanced distribution automation schemes.

By using the advanced control and protection functions, the GVR can also be used in applications where reclosers have not traditionally been used such as closed rings and under frequency load shedding schemes.

There is up to 10 years or 10 000 operations between services.

Type tests

- general: by ANSI C37.60,
- electromagnetic: by IEC 801,
- protection: by IEC 255.

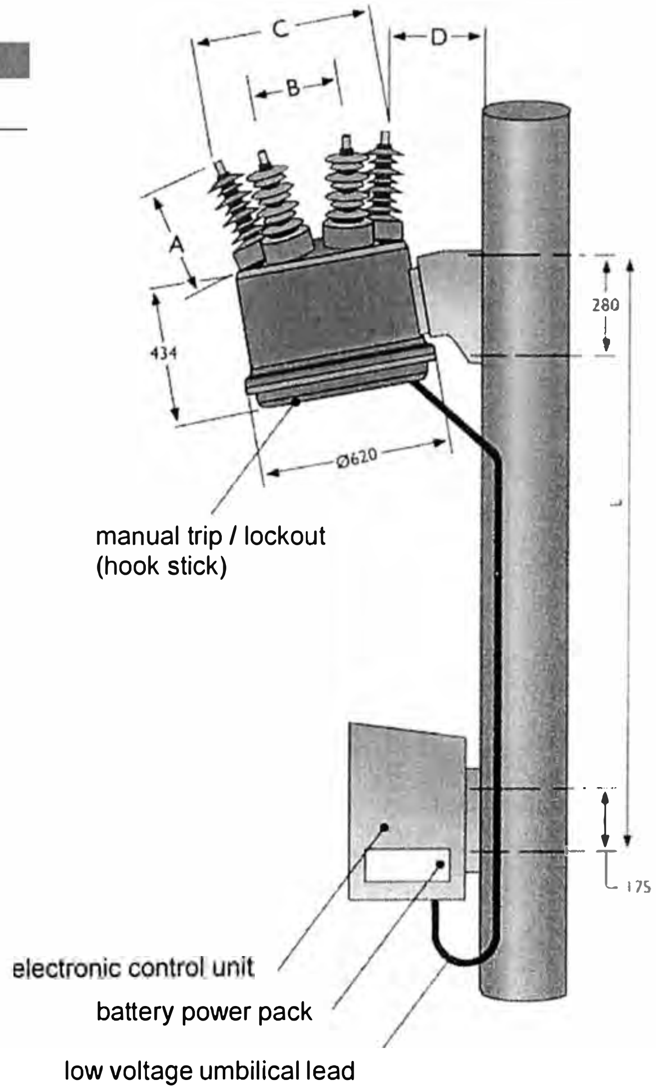
Type		GVR15	GVR27	GVR38
maximum system voltage	kV	15,5	27	38
rated current	A	630	630	630
interrupting current	kA	6/12,5	12,5	8
impulse voltage withstand	kV	110	125(150)	150 (internal) 170 (external)
power frequency withstand				
dry	kV	50	60	70
wet	kV	50	50	60
rated gas pressure for above		atmospheric	atmospheric	0,3 bar(gauge)
number of operations		10 000	10 000	10 000
weight	kg	145	145	155

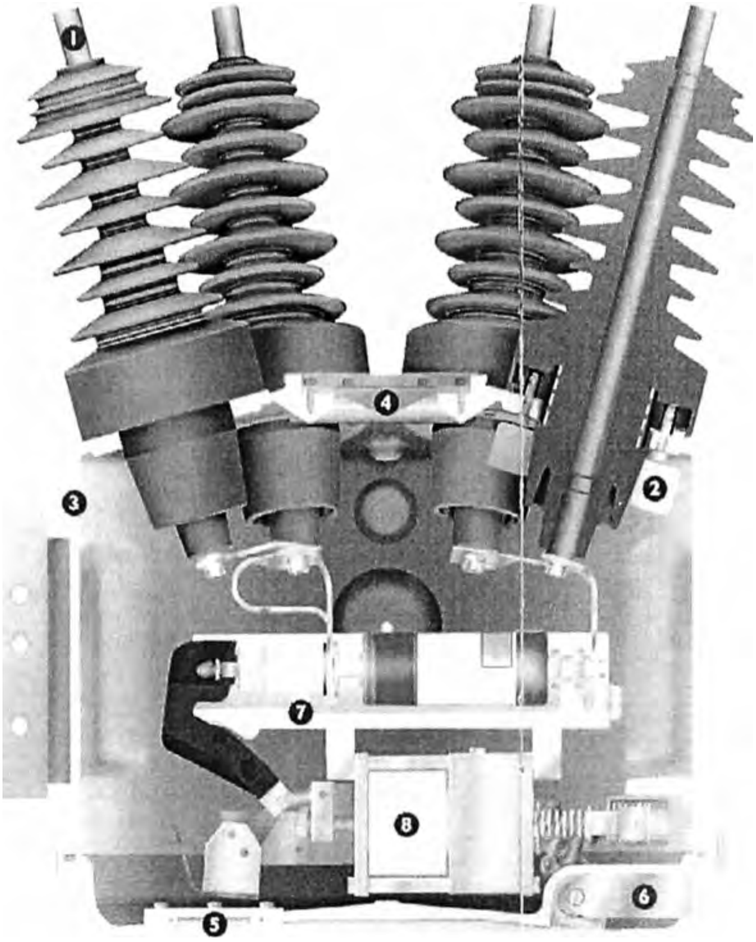
Bushing dimensions

Voltage	Creepage	A	B	C	D
up to 27 kV	830 mm	369	286	571	298
38 kV	1178 mm	469	312	623	412

Umbilical dimensions

L	Cable length
up to 2000	3000
2001 – 3000	4000
3001 – 4000	5000
4001 – 5000	6000





Main features:

① Single piece, aluminium or copper-cored EPDM or silicone rubber bushings, with grooves to take optional wildlife guards / HV boots.

② Current transformers are mounted within the tank's controlled environment, while capacitive voltage dividers moulded into the bushings on both sides of the GVR.

③ Aluminium housing with lightweight, moulded base plate, secured by stainless steel bolts and incorporating rubber "O" rings seals.

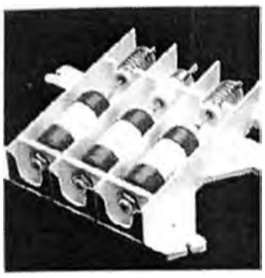
④ Optional pressure-relief disc, to comply with IEC 298 Appendix AA, offers the highest levels of safety.

⑤ Mechanical ON / OFF position indication visible through clear viewing window from ground level.

⑥ Hook stick-operated manual trip and lockout control.

⑦ A single moulding supports the three phase vacuum interrupter assembly, magnetic actuator mechanism and one-piece drive beam.

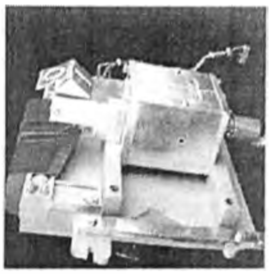
⑧ The single coil magnetic actuator is based on a solenoid plunger, held in the tripped or closed position by a permanent magnet.



Vacuum bottles in monoblock

Umbilical plug and socket

Position indicator

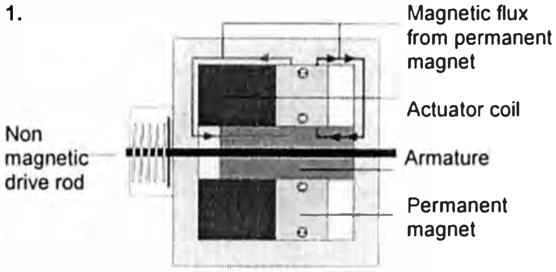


Magnetic actuator

Single coil magnetic actuator

The actuator coil is energised in one direction to power close the GVR and in the opposite direction to open it by de-latching the holding force. This is a unique feature of the single coil actuator design used in the GVR and ensures reliable tripping operation under all battery conditions and even for manual trip.

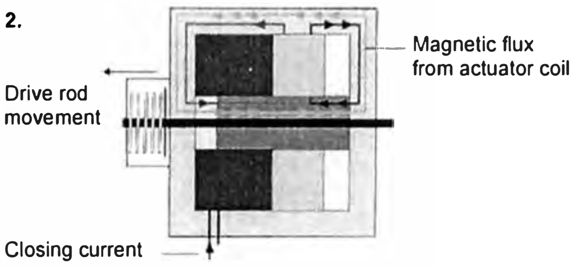
1.



Closing

The bi-stable design ensures that the plunger is held back in the open position (1) until the solenoid current rises above the level required to guarantee closure. Once the holding force is overcome (2), the circuit breaker closes positively (3), due to the stored energy in the solenoid and permanent magnets.

2.



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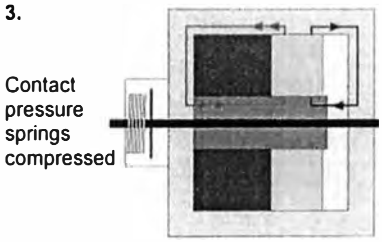
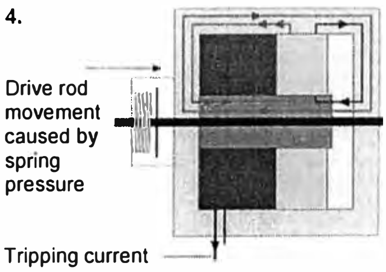
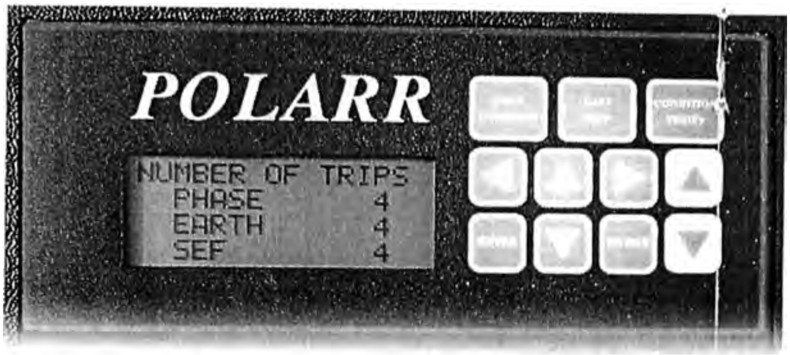


Tripping

The solenoid is energised in the reverse direction (4) to overcome the magnetic hold-on force and de-latch the actuator. Opening is then completed by the energy stored during the closing stroke in the contact pressure and opening springs and is completely independent of the power supply during electrical opening, and of the operator during manual opening. The energy required to trip is approximately 1 / 30th of that required to close.

4.





Principle of operation

The Polarr is the standard relay package for the GVR. It measures the 3 phase and residual currents using CTs located in the GVR, and performs auto-reclosing over current, earth fault and sensitive earth fault protection. The low power, microprocessor architecture of the Polarr is unique to the power industry. Its design has been perfected over several years and offers the user significant benefits through the elimination of the need for any external power supply. In addition to this, the Polarr offers several advanced auto-reclosing functions in a comprehensive but cost effective package.

Weather protection

The Polarr relay and lithium batteries are housed in a control box located on the pole at ground height underneath the GVR. Connection to the GVR is via an umbilical cable and weatherproof plug and socket that is used to carry the CT currents and the GVR control signals. The IP 67 sealed control box is made from hot dip galvanised steel, with an outer double skinned sun shield of polyester-coated galvatite. It protects against the harshest environment and maintains an even internal temperature keeping the relay condensation-free.

Lithium batteries

High energy density lithium battery technology makes the GVR with Polarr ideal for applications where an auxiliary power supply is not available.

Programming protection settings

Protection settings can be programmed via the dot matrix display and keypad or downloaded though the serial port from a hand held Psion organiser or directly from a notebook computer using libraries of settings created in Windows based software.

ta logging

Historical, diagnostic and load current data can be accessed through the local display or the serial port. The Polarr history is held in non-violate memory, and includes the time and date of the last 20 sequences together with number of trips in the sequence and fault magnitude of each of the elements.

Minimum trip currents

The multi-ratio CTs located in the GVR and a wide range of programmable minimum trip settings ensure that the GVR and Polarr can be used at any point in the network, from substation through to the feeder ends with the earth fault currents as low as one ampere.

Short cut keys

In addition to large, clear control keys, LED indication and a menu-driven display for entering settings and viewing historic data, the front panel also incorporates three push-buttons for instant access to load current, fault target and battery condition information.

Sequence co-ordination

The Polarr's advance sequence co-ordination logic and fast response times of the relay allow co-ordinating delays as low as 60 ms to ensure that only the recloser closest to the fault operates.

Local control

Push buttons are provided for the standard auto-recloser functions, while separate keys and LED indication are used for the circuit breaker control.

Remote control

All of these functions are also available through a parallel SCADA port on the back of relay, accessible through a gland plate in the control box. Voltage free contacts and opto-isolated inputs offer a standard interface to a third party RTU of the customer's choice. Alternatively, an enlarged control box to house an RTU and rechargeable battery pack can be provided.

Operating sequence

Up to 4 trips to lockout are available for over current, earth fault and sensitive earth fault sequences. The time between GVR clearing the fault and reclosing is known as the dead time and is selectable for each trip. If the fault is temporary, the protection will begin to reclaim after reclosing. If the fault is permanent, the GVR will lockout after the last trip. A Cold Load Pickup feature avoids spurious tripping when manually closing onto de-energised loads.

trips to lockout	1 to 4
dead times (s)	0,25 to 180
reclaim times (s)	5 to 180

inimum trip settings

The GVR is supplied with multi-tapped protection CTs with ratios of 300/200/100:1. Minimum trip settings selections within the relay ensure suitable operation at any point in a network.

	Polarr
I > (x I_n)	0,2 to 3,2
I_o > (x I_n)	0,1 to 1,6
I....> (x I_n)	0,01 to 0,16

Time current characteristics

Time current characteristics are programmable for every trip in the sequence. There is choice of time dependant curves of definite time. The curves can be modified using time multipliers, additional delays and minimum response times. Instantaneous protection offers the fastest fault clearing times and can be used with additional delays for sequence co-ordination.

	Polarr
curves (t>)	IEC 255 (IDMTL, VIDMTL, EIDMTL) & McGraw Edison
inst. I >>(x I_n)	1 to 20-krát

Accessories

Optional extras

- surge arrestors for lightning protection
- aluminium bushing conductor material
- fully insulated HV joint boots
- pressure relief device for internal arc withstand to EATS 41-27 & IEC 298 appendix AA
- metering CTs
- SF_6 pressure sensor and indication
- umbilical lead length
- user programmable protection curves

Accessories

- Psion hand held terminal for data input and retrieval
- software and RS 232 cable for data input, retrieval and storage using IBM PC
- portable test set
- dummy sealing plug for use when umbilical lead disconnected from housing
- gas filling equipment
- hand held pressure gauge
- SF_6 gas detector

Accuracy

- protection: ± 5% of time to IEC 255
- instrumentation: ± 5 % standard with capacitive voltage dividers or option for ± 2 % with separate VT

ANEXO B

COMPARACIÓN DE INTERRUPTORES SF6 vs VACÍO-ABB

SF_6 or vacuum?

Choosing the right MV circuit-breaker

Guenter Leonhardt, Mauro Marchi, Giandomenico Rivetti

More than three decades of experience in developing SF_6 and vacuum circuit-breakers, accompanied by increasingly close cooperation between the participating research centers, gives ABB a strong advantage when it comes to deciding which technology is best for a given application. The pioneering role played by the company uniquely qualifies it to pursue R&D on both fronts with the goal of pushing performance levels to the limit. The sum of this research work, coupled with unrivalled knowledge of the marketplace, puts ABB in a position to offer unbiased advice and assistance to customers searching for the switchgear that best suits their needs.

Approximately 35 years ago, in the mid 1960s, two new breaker technologies, one using SF_6 gas and the other vacuum as its arc quenching medium, were introduced to the market. Research and development work on both technologies has continued unabated since then, and today it can be said that, together, they have all but replaced the older types of switchgear. There is, however, not always agreement on which criteria should be used when choosing one of these two dominant technologies. Instead of an objective selection based on real-world characteristics, the choice i very much driven by the circuit-breaker manufacturer.

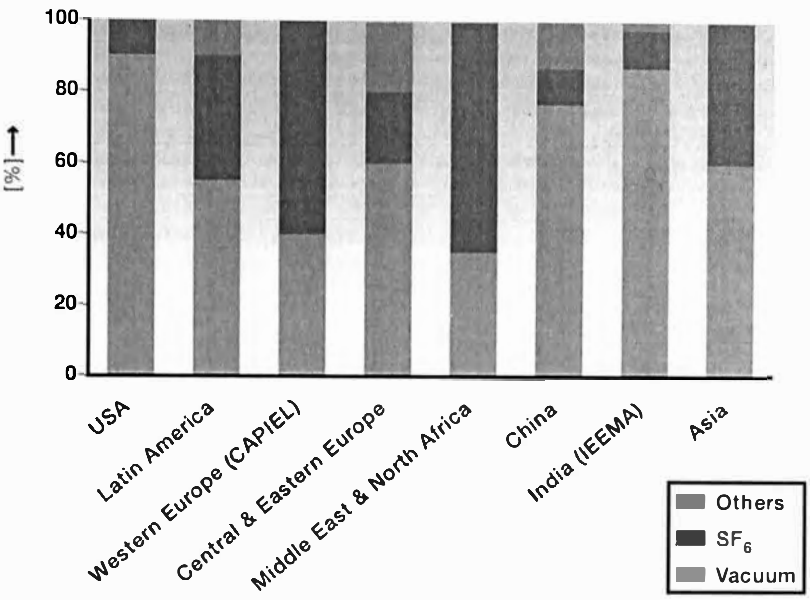
SF_6 and vacuum switchgear enjoy varying market success in the different parts of the world 1; whereas Europe and most of the Middle East countries tend to favor SF_6, China, Japan and the U A definitely prefer vacuum. In other regions, the two technologies are equally popular. Bulk-oil and minimum-oil technologies are still used in China, Eastern Europe, India and Latin America, but trends clearly indicate that these technologies will disappear very soon, to be replaced by SF_6 and vacuum.

As shows, ABB concentrates today almost entirely on the two dominant technologies, and is equally present in the market with both SF_6 and vacuum.

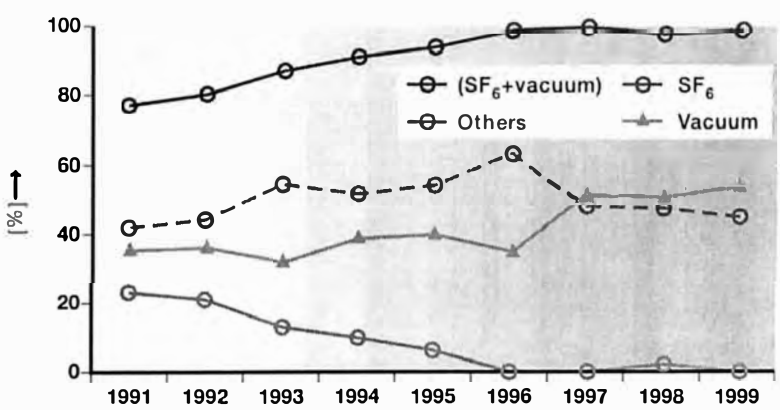
Experience with more than 300.000 MV circuit-breakers of both designs installed worldwide, backed up by over 30 years of intensive involvement in research [1], has convinced ABB that the two technologies are entirely complementary, though in some cases their different designs can be seen as alternatives. Based on this conviction that SF_6 and vacuum have equally important roles to play, the company has continued to force the development of both, and hence, as the world's largest manufacturer of MV circuit-breakers, occupies the unique position of being able to provide unprejudiced advice and assistance in the selection of switchgear for any special application.

The decision by ABB to pursue both technologies with equal emphasis has produced several important benefits. First and foremost, a profound knowledge of the behavior of the two technologies has led to better service for customers. At the same time, keen competition between the company's research laboratories has led to top team performances, the exchange of information between them having extracted the maximum synergy from parallel work. Finally, it was recognized at an early stage that it would be of great advantage to both user and manufacturer if the circuit-breakers were constructed so as to be completely interchangeable, as shown by 3.

Proceeding in this way, all new developments are equally advantageous to both technologies. The most important developments to come out of this



1 Worldwide market for MV circuit-breakers by region (1998)



2 MV circuit-breakers manufactured by ABB

approach are the use of magnetic actuators as the operating mechanism and the integration of sensors in the switchgear panels. With total interchangeability, users are faced with easier choices and structural factors are no longer a major consideration in their decisions.

Arc-interrupting characteristics

SF_6 circuit-breakers

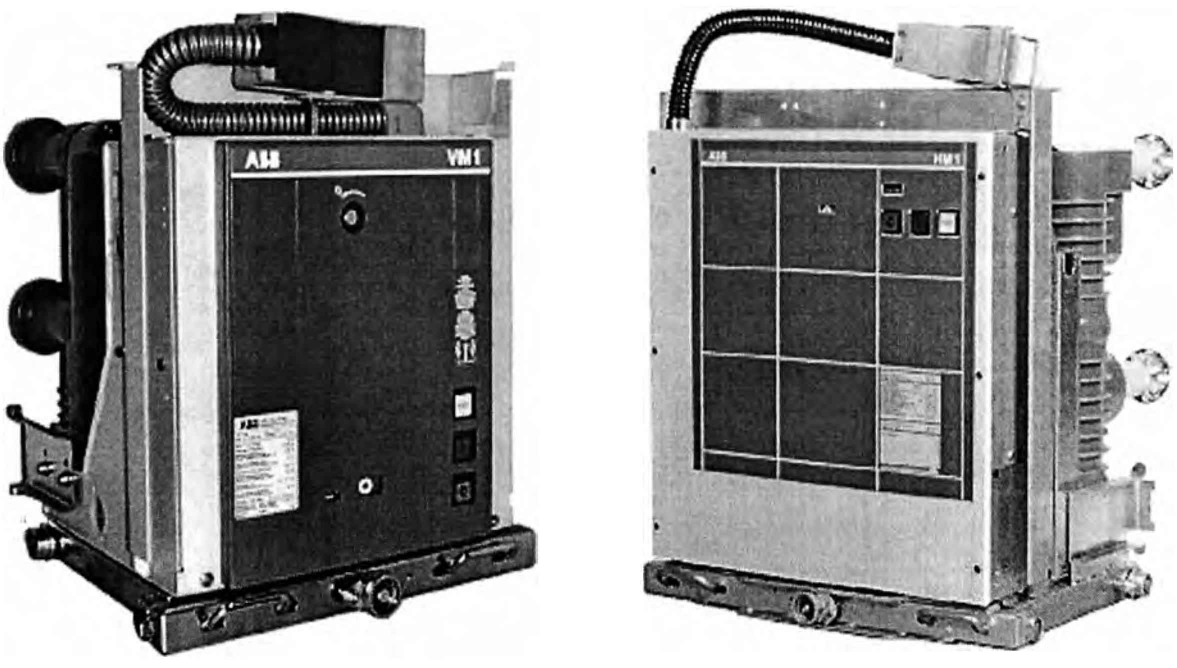
Sulfur hexafluoride (SF_6) is an artificial inert gas with excellent insulating properties and exceptional thermal and chemical stability. These characteristics of the gas have led to its widespread use in both HV and MV switchgear, both of which exhibit very high performance and reliability as a result.

The specific advantages of SF_6 gas in electrical engineering applications have been widely recognized since the early 1930s, but it was only in the late 1950s that the first high-voltage SF_6 insulated circuit-breakers were developed and installed. SF_6 medium-voltage circuit-breakers followed some years later.

The first generation of MV SF_6 circuit-breakers employed a dual-pressure gas system. Second-generation designs included the pressure differential necessary to create the gas flow, this being provided by a mechanically driven piston which compressed a small volume of gas. The piston was integrated in the moving contact assembly. Such 'puffer-type' circuit-breakers required a relatively powerful mechanism [2]. The third generation of designs produced the gas flow by utilizing the energy contained in the arc. This 'self-blast' circuit-breaker design resulted in significantly less energy being required for its operation.

The more than 30 years of ABB experience and research associated with the puffer and self-blast circuit-breakers have now culminated in a new and very efficient design. This so-called 'auto-puffer' combines the advantages of both previous designs. The auto-puffer circuit-breaker operates as a pure puffer device when interrupting currents up to 30% of the maximum rated breaking capacity and as a self-blast interrupter at higher levels. The auto-puffer requires only a minimum amount of energy from the operating mechanism, but offers the high

VM1 vacuum (left) and HM1 SF_6 medium-voltage circuit-breakers with magnetic actuator



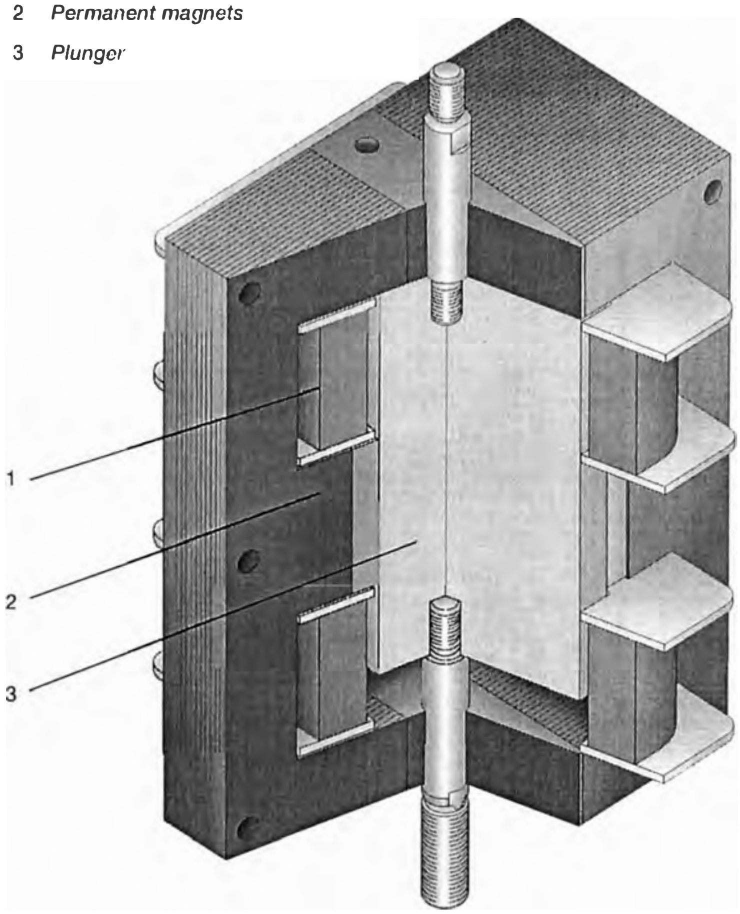
performance levels of the self-blast type. Reduced arc energy dissipation at both low and high (short-circuit) currents ensures a longer electrical life than either of the former designs. This performance is obtained without jeopardizing the total absence of chopping currents, which is a key characteristic of the self-blast technique. The design of the mechanism has been optimized to generate only enough pressure to ensure the safe interruption of currents in the range in which the puffer technique is operative. Consequently, small inductive currents are effectively interrupted with overvoltage factors lower than 2.5 pu.

Cutaway view of the magnetic actuator

1 *Coils*

2 *Permanent magnets*

3 *Plunger*



Vacuum circuit-breakers

As early as the beginning of the last century, the interruption of current in a vacuum was recognized as an 'ideal' switching technique. However, several practical difficulties led to it being ignored for almost three decades. One of the fundamental problems was the manufacture of a suitable insulating enclosure, which had to be hermetically sealed for life. This problem existed through a number of decades until, in the early 1960s, a solution using glass enclosures was developed. Curiously, the fundamental technology of blown-glass containers had been commonly available for centuries. A further step forward came with the development of alumina (Al_2O_3) ceramics, a material which possesses a much higher resistance to cyclic temperature stresses.

Finding a suitable material and form for the circuit-breaker contacts was also a considerable problem. The contacts had to exhibit a high resistance to arc erosion during both opening and closing operations, and any erosion had to be diffuse and even over the whole contact surface. The contact material had to have a low propensity to weld during closing as well as when closed. Low current chopping characteristics when interrupting small currents was also important, as was an adequate gettering effect. The search for a suitable material showed that chromium possessed most of the required properties. Further research showed composite material of copper/chromium to be the most suitable and best able to satisfy the basic requirements. Cu/Cr with a chromium content of between 20% and 60% is now the standard material for contacts, and is used by all manufacturers of vacuum circuit-breakers.

The mechanism of charge carrier formation gives a vacuum circuit-breaker the inherent ability to extinguish current arcs of small to medium values automatically when the current passes through zero. A satisfactory interruption of short-circuit currents, however, requires additional design measures. The initial designs used a specially shaped electrode to produce a radial magnetic field in the arc contact area. This magnetic field, reacting with the arc current, forced the arc root to move continually around the contact surface, thus preventing local overheating and uneven wear.

A further design improvement, aimed particularly at increasing the current interrupting capacity to extremely high short-circuit currents, was the development of the 'axial' magnetic field. Again a specially designed electrode is employed to generate an axial magnetic field, which distributes the arc root homogeneously over the whole of the contact area.

Common trends in SF_6 and vacuum circuit-breaker development

ABB SF_6 and vacuum circuit-breakers have been used for many years in medium-voltage switchgear and service experience has shown them to be reliable, almost maintenance-free and safe under operating conditions. Innovations in both technologies have continually improved their efficiency, reduced their overall dimensions and, most importantly, reduced the amount of energy required to operate them.

This reduction in operating energy has led to the development of an entirely new design of operating mechanism, the permanent magnet actuator.

Magnetic actuator

The operating mechanism of a circuit-breaker has the apparently 'simple' function of moving the contacts from the closed to the open position or vice versa and, when the required position is reached, of ensuring that the contacts remain in that position until a definite command to again change position is given. The operating mechanism is thus a typical bistable actuator. This function has been performed with a high degree of reliability and surety for many years by mechanical spring and latch mechanisms. However, the opportunities now offered by developments in power electronics have led to the search for a more flexible and more readily controllable operating device. Of course, an essential prerequisite of any new system was that it had to guarantee at least as good or better performance, in terms of reliability, safety and durability, than the traditional spring-based mechanism.

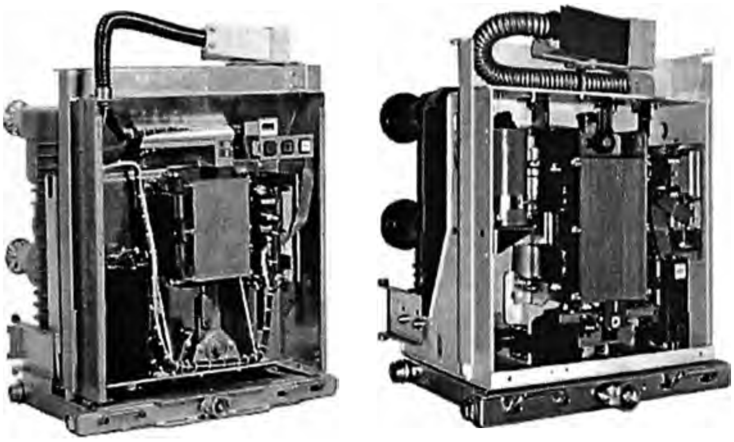
An appropriate solution has been found in the 'magnetic actuator'. A specially designed system combining electromagnets with permanent magnets provides the operating energy for the movement of the contacts as well as the essential bistable characteristic. The vacuum and the SF_6 interrupters are held in either their open or closed positions by the force of a permanent magnet and this without the need for any external energy. The change of status of the moving contacts is brought about by a change in direction of the magnetic field resulting from the energizing of the electromagnets, which are the control elements of the actuator. Modulation of the current supply to the electromagnets allows the energy developed by the system to be adjusted to the requirements of different types and ratings of circuit-breakers.

The resulting operating mechanism is considerably simpler in construction than the conventional mechanical system. The drastic reduction in the number of parts inherently reduces the susceptibility to failure, and the level of maintenance required by this operating mechanism is reduced to the very minimum. shows the construction of such an actuator with its fixed laminated iron core, permanent magnets, steel armature and closing and opening coils. All auxiliary functions, such as interlocking, signaling, tripping, closing, etc, are provided electronically; self-diagnostic facilities are also included. An electrolytic capacitor provides the surge power required for the opening and closing coils.

Basic construction of the switching devices

The new vacuum and SF_6 magnetically actuated circuit-breakers are fully interchangeable with each other as well as with previous designs. This interchangeability is of considerable importance to plant operators as it allows existing switchgear to be re-equipped at minimum cost.

View of the VM1 vacuum (right) and HM1 SF_6 medium-voltage circuit-breakers showing the small number of components



4 and 5 show clearly the very small number of components used, a fact that significantly reduces the potential for failure.

Simplicity is also a feature of the embedded vacuum pole and the SF_6 interrupter using the auto-puffer technique, specially adapted for medium-voltage applications 6.

Thanks to the embedding technology there is no need for special support structures for the interrupter or its terminals.

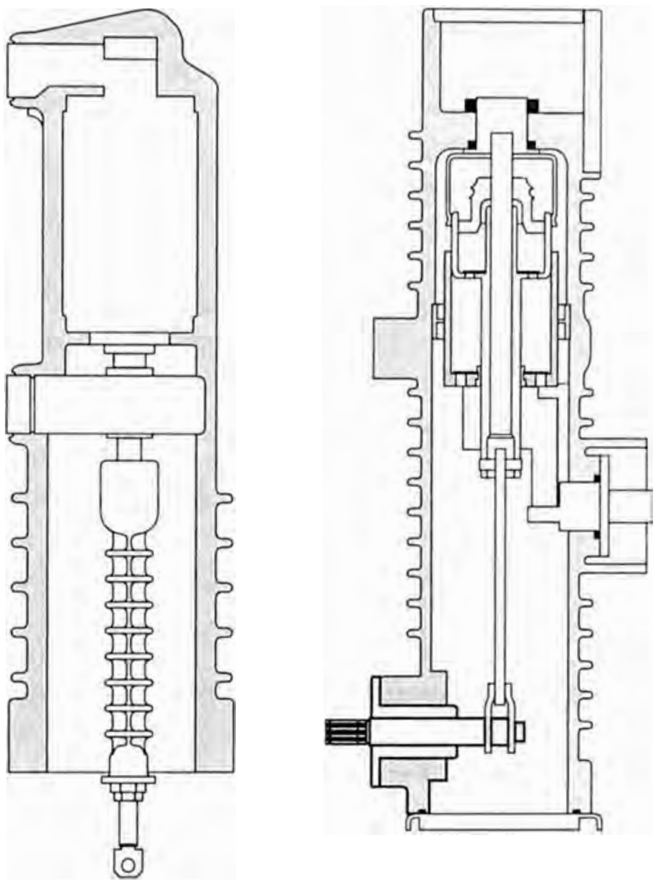
Rapid switching

An important property of the magnetic actuator that has already been mentioned is the versatility of its control functions. Exploitation of this flexibility opens the door to new solutions to key problems in electrical distribution, problems which until today have been solvable, if at all, only at great expense. One of these issues is the rapid transfer-switching between energy sources in the event of a fault in one system. This problem has been dramatically emphasized in the last few years by an exponential increase in power-quality sensitive loads, mostly due to the use of electronic equipment. The present solution, based on power electronics devices, is very efficient from the technical point of view but also very expensive. Introduction of the magnetic actuator has made it possible to accelerate the operation of an MV circuit-breaker to the absolute minimum, that is to the pure arc extinction time. Using magnetically actuated medium-voltage circuit-breakers and appropriate basic electronics, it has been possible to reduce power source transfer-switching times to less than 40 ms. This elapsed time is so short that it solves most of the problems of sensitive loads and at a cost which is very competitive compared with the power electronics based solutions [5].

Synchronous circuit-breaker

The availability of these new circuit-breakers with their magnetic actuator mechanisms has another important advantage: they provide the basis for synchronous switching. This switching technique involves the circuit-breaker poles being independently operated, with each pole opened or closed at the best point in time relative to the current and/or voltage conditions prevailing in the relevant phase. Synchronous switching minimizes the electrical and mechanical stresses which arise on both the supply and load sides of the circuit being switched and in the circuit-breaker itself when the current is interrupted. With synchronous switching, the amount of energy which has to be dissipated in the interruption chamber is minimized and any overvoltage resulting from the switching operation is greatly reduced. All of these advantages result from the precise control of the circuit-breaker operation made possible by the magnetic actuator. The control accuracy is so great that it is possible to synchronize the completion of the moving contact travel with the current zero-crossing in each phase. Furthermore, synchronous switching minimizes, theoretically even reduces to zero, the inrush current peaks and overvoltages that occur during the energization of inductive or capacitive loads. Given the type of load, these results are obtained by controlling the closing of the contacts to correspond with either the current or voltage maximum. The closing and opening operations described are performed with a maximum tolerance of ± 0.5 ms and ± 1 ms, respectively. These figures are a true measure of the value of the technological breakthrough achieved by the combination of digital electronics with the magnetic actuator.

6 Section through the embedded vacuum pole (left) and the auto-puffer SF_6 pole



These developments will result in improved reliability for the entire electrical system, greater safety for the personnel, and cost reductions due to the minimization of electrical stress and wear on the electrical equipment [6].

Integration with sensors and electronics

The hardware and software presently available for use with the magnetically actuated circuit-breakers allow a further step forward in the direction of complete functional integration. With the appropriate software and the necessary current and voltage sensors, the direct integration of the protection functions in the circuit-breaker control system is now possible. This makes the circuit-breaker a fully automated device for protection and switching functions and achieves the goal of maximum reliability – the result of minimization of the component interfaces. This total integration of the core functions in switchgear has already been shown to be the correct path to follow in medium-voltage secondary distribution applications, just as it is already the current state of the art in the field of low voltage equipment.

Technical performance

Electrical and mechanical endurance

Both SF_6 and vacuum circuit-breakers can be considered maintenance-free. High-quality SF_6 circuit-breakers as well as high-quality vacuum circuit-breakers fulfil the requirements for class B circuit-breakers as given in the IEC 60056 standard [3]. This states that:

'A circuit breaker class B (in the IEC draft document, in the future it will be E2) is a circuit breaker designed so as not to require maintenance of the interrupting parts during the expected operating life of the circuit-breaker, and only minimal maintenance of its other parts.' Based on service experience, the IEC standard establishes the number of operations that a circuit-breaker shall be capable of performing under the severe service conditions associated with an overhead line connected network and including auto-reclosing duty.

The standard prescribes two alternative test cycles for the verification of electrical endurance performance of a circuit-breaker. The test cycle in accordance with List 1 is the preferred one; the test cycle of List 2 may be applied as a valid alternative for circuit-breakers for use in solidly grounded systems. The severity level of these two test cycles is regarded as identical.

Reliability of dielectric media

Modern SF_6 and vacuum circuit-breakers are sealed for life; diagnostic systems for the purpose of measuring the gas pressure or the vacuum level are therefore unnecessary.

Switching overvoltages

Any switching overvoltages generated by circuit-breakers using either technology are contained within such limits as not to present any danger to connected equipment or installations.

Due to their inherently soft interruption characteristics SF_6 circuit-breakers offer this level of performance without the need of any additional devices.

Vacuum circuit-breakers using modern contact materials also exhibit low chopping currents; however, in exceptional cases, and depending on the characteristics of the individual installation, a detailed study of the system parameters may be necessary in order to determine if specific voltage limiting devices are required.

Environmental impact

The operation of either circuit-breaker type presents no health hazard to personnel. In the unlikely event of a major malfunction, overpressure valves built into the SF_6 circuit-breakers would respond, while vacuum circuit-breakers would be subject to no more than implosion phenomena. Experience has also shown that any emission products from either type of circuit-breaker do not constitute a toxic hazard. The component materials of both types of apparatus can be readily recycled at the end of their service lives. The Kyoto Protocol to the United Nations Framework Convention on Climate Change (10th December 1997) has established that emissions of six gases considered to be a likely cause of global warming, SF_6 among them, need to be reduced. It was therefore necessary to analyze the greenhouse gas (ie, SF_6 and CO_2) emissions occurring as a consequence of the manufacturing process and the power losses in service. The Life Cycle Assessment (LCA) that was subsequently carried out for vacuum and SF_6 circuit-breakers leads to the following conclusions, which are substantially the same for both types of equipment.

The impact of the manufacturing and the service phases are to be considered separately. Consideration of the SF_6 circuit-breaker shows that the environmental impact during the entire manufacturing phase is more than 100 times greater than the environmental impact of the unit throughout a 30-year total life cycle due to the fact that medium-voltage SF_6 breakers are sealed for life [4]. The production of the copper and insulating components of the circuit-breaker is the predominant contributor to the environmental impact throughout the manufacturing phase.

As regards the environmental impact during service, based on an assumed 30-year service life and an average load current of 20% of the rated current it can be calculated that the service phase has an environmental heating effect of more than 7 to 8 times that caused during the manufacturing phase. This is due to the resistance losses in the circuit-breaker. The analysis shows that the environmental impact of the SF_6 gas itself, relative to the impact of the complete apparatus over its complete life cycle, is only about 0.1% of the total. When considering vacuum circuit-breakers, it is evident that because of the quantity of copper and the number of insulating components, as well a the main circuit resistance, the results are very close to those for the SF_6 circuit-breaker.

Considering the global warming effect alone, it can be concluded that the impact is determined essentially by the main circuit power losses. However, these losses are in turn fully negligible when compared with those caused by the cables, connections and all the other apparatus which make up the electrical distribution system.

Specific switching applications

Overhead lines and cables

When applied to the onerous duty of switching and protecting overhead line distribution networks, in which the fault currents are distributed over the whole current range, both technologies provide adequate margins over and above the maximum required by the relevant standards and in normal service practice.

Transformers

Modern vacuum circuit-breakers as well as SF_6 circuit-breakers are suitable for switching the magnetizing currents of unloaded transformers with overvoltages lower than 3.0 pu. In special cases, for instance when vacuum circuit-breakers are used for switching dry-type transformers in industrial installations, the use of surge arresters is to be recommended.

Motors

When choosing circuit-breakers for motor-switching duty, attention should be paid to the problems of overvoltages during operation. The target limit for overvoltages of less than 2.5 pu is obtainable with both technologies. Where vacuum circuit-breakers are used for switching small motors (starting currents less than 600 A), measures may be necessary to limit overvoltages due to multiple re-ignitions; however, the probability of this phenomenon arising is low.

Capacitor banks

Both technologies are suitable for restrike-free switching of capacitor banks. When capacitors must be switched back-to-back, reactors may be necessary to limit the inrush currents. The synchronous control of circuit-breakers is an effective solution to this problem. SF_6 is specifically recommended for applications with rated voltages higher than 27 kV.

Arc furnaces

Arc furnace switching is often characterized by frequent operation at high current values and short intervals. Vacuum circuit-breakers are particularly suited to these service conditions.

Shunt reactors

SF_6 circuit-breakers are suitable for switching with overvoltages generally lower than 2.5 pu. Where vacuum circuit-breakers are employed, it may be necessary under certain circumstances to take additional measures to limit overvoltages.

Railway traction

In principle, both interrupting technologies are well suited for this duty; however, in the case of low-frequency applications (eg, 16.67 Hz), vacuum circuit-breakers are to be recommended.

Matching the circuit-breaker to the task

Thirty years of experience in developing, manufacturing and marketing both SF_6 and vacuum medium-voltage circuit-breakers worldwide has yielded up ample evidence that neither of the two technologies is generally better than the other, and especially that they are complementary from the application point of view. Economical factors, user preferences, national 'traditions', competence and special switching requirements are the decision-drivers that favor one or the other technology. Typical of such special applications is the switching of dry-type transformers, small-size motors, capacitors, arc furnaces, shunt reactors and railway traction systems. The need for 'frequent switching' or 'soft switching' can be an additional element influencing the choice. In such cases, a comprehensive study of the planned installation may be needed to find the best answer. ABB has the know-how and experience necessary to provide unbiased advice and assistance to users in choosing the circuit-breaker most suitable for any particular application.

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ANEXO C

DISEÑO DE SUBESTACIONES PRESERVANDO EL MEDIO AMBIENTE-HITACHI

Environmentally-conscious Substation Systems Designed in Response to Global Warming

Kazuhiko Nagasawa
Tetsuya Kato
Tomomichi Ito
Tsuyoshi Yamazaki

OVERVIEW: At The Third Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change held in Kyoto in 1997, gases that contribute to global warming were specified, and since then the needs of society regarding environmental conservation have become more and more urgent. Aiming at meeting these needs in the field of railway systems, which are fundamentally benign to the global environment, Hitachi has developed various commercial transformer systems for railway use that contribute to further reduction of greenhouse-gas emissions. In particular, two key products were developed: a regenerative energy absorbing equipment for railway systems that use lithium-ion batteries like those applied in hybrid vehicles; and a completely sulphur hexafluoride (SF_6)-gas-free, 72-kV dry-air insulated switchgear unit that uses absolutely no SF_6 gas (which has a high global-warming potential and has been conventionally used as the insulating medium in transformers). By applying these products, we have been able to construct an environmentally-friendly transformer system for electric railways.

INTRODUCTION

IN accordance with the recent view of society, it is being demanded that electricity substation systems for railway use are constructed to be even more environmentally-friendly than they have been up till now. With satisfying this social need in mind with reducing emissions of greenhouse gases as our leading motive, Hitachi has developed various environmentally-friendly products for railway electricity substation systems. These products include a regenerative energy absorbing equipment for railway systems using a lithium-ion battery, fully gasless (no sulphur

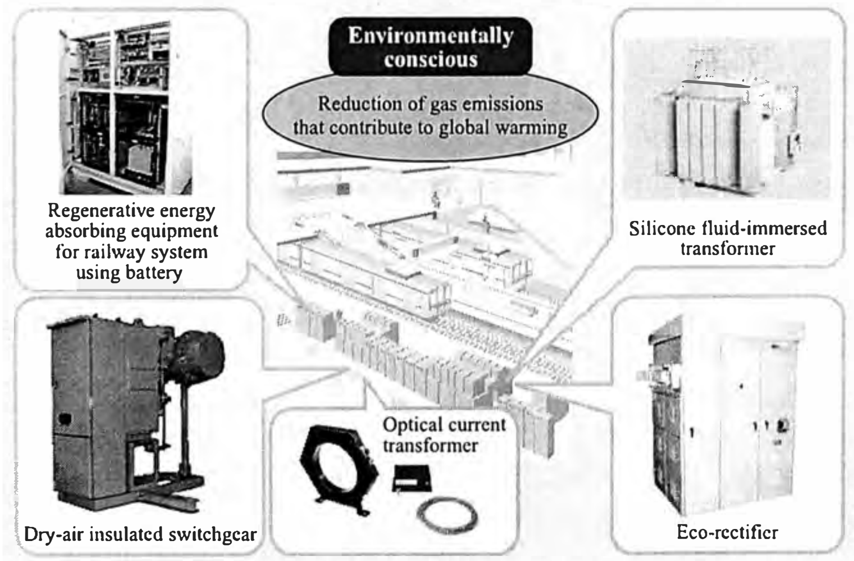


Fig. 1—Hitachi's Product Line-up for Configuring Environmentally-conscious Substation Systems.
By applying products that aim to reduce gas emissions that contribute to global warming, Hitachi has configured an environmentally-conscious substation system.

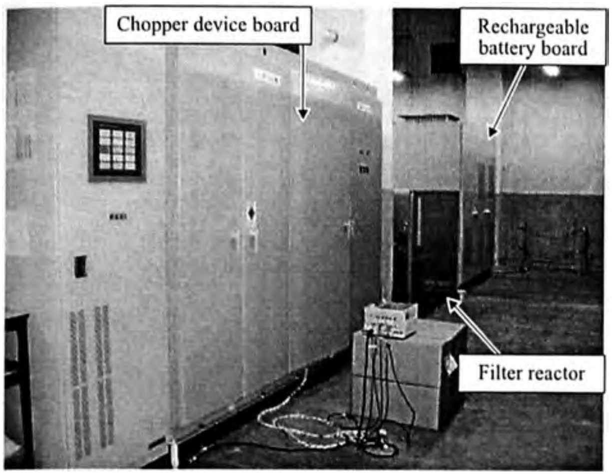


Fig. 2—Scene from Field Tests on Regenerative Energy Absorbing Equipment Using Batteries.
The specification of the field-test equipment consisted of two multi-layered chopper IGBTs (insulated-gate bipolar transistors), four serial and five parallel DC 1,500-V lithium batteries, and operation at 500 kW (operates for 15 s in a cycle of 180 s).

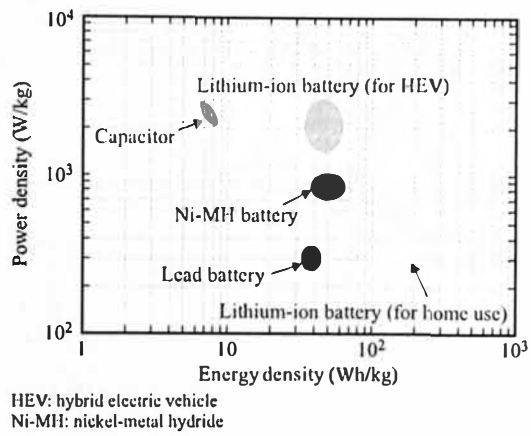


Fig. 3—Performance Comparison of Battery Media.
The performance of a rechargeable batteries, i.e. a lithium-ion battery for HEV use, an Ni-MH battery, and a lead battery, are compared. It is clear that the lithium-ion battery is designed for rapid charging and discharging, and it is well suited to loading by electric trains.

hexafluoride) dry-air-insulated switchgear, a silicone-fluid-immersed transformer using silicon liquid as an insulating medium, and an optical current transformer that contributes to reducing industrial waste and improving recyclability. In the following sections, each of these products and their respective applied technologies are explained.

ENVIRONMENTALLY-CONSCIOUS POWER-ELECTRONICS EQUIPMENT

Hitachi is currently developing a regenerative energy absorbing equipment using batteries as a converter for electrical power (DC: direct current) substations used for railway systems that take account of environmental issues, and an eco-rectifier has already been commercialized.

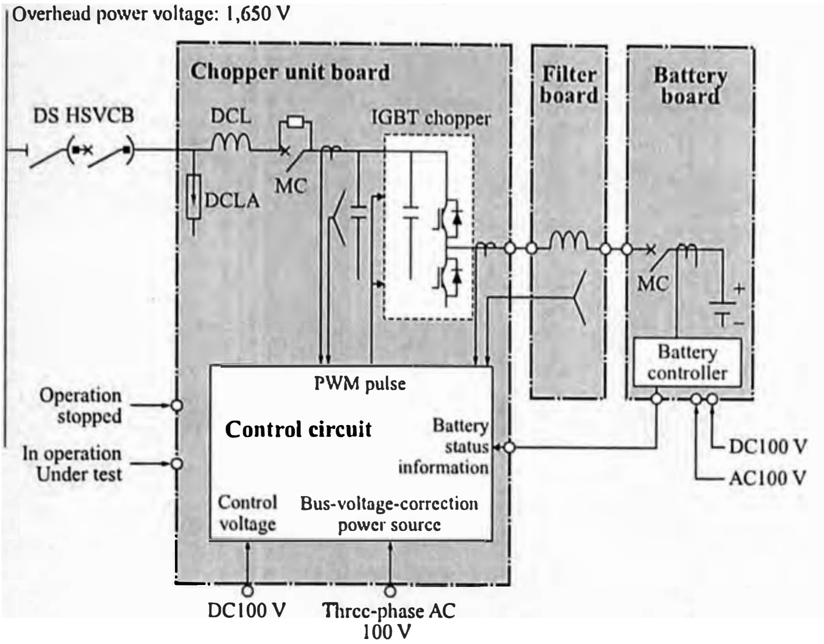
Regenerative Energy Absorbing Equipment Using Batteries

Background to development

In recent years, Hitachi has commercialized and is implementing a regenerative inverter and a friction-consuming-type regenerative energy absorbing equipment as a measure against the regenerative lapse that occurs in the regenerative trains being developed by various train companies. These devices, however, have both good points and bad points. Accordingly, as a device with the good points of either device, a regenerative energy absorbing equipment using lithium-ion batteries was developed. This unit not only applies conventional measures against regenerative lapses but also applies a voltage-drop measure utilizing an electromotive voltage (for improving acceleration performance of a train). As a result, this unit shows promise in a wide range of applications. At present, with the cooperation of train companies, we have completed field tests of this unit installed at an actual DC electromotive-voltage transformer substation, and commercialization of this unit is continuing (see Fig. 2).

Adoption of Rechargeable Battery

The battery for use in the regenerative energy absorbing equipment is a lithium-ion type. Developed for use in hybrid vehicles, the lithium-ion battery is presently considered suitable to meet the needs for large current charge and discharge as well as large storage capacity. A performance comparison of various battery mediums is shown in Fig. 3. The characteristics of a lithium-ion battery are both high power density and high energy density, so it is superior in those terms in comparison to other battery media. In addition, according to modifications to materials used, etc., long-lifetime technologies for the lithium-ion batteries are well established, and the possibility of using them under the loading conditions and established environments of power substations have been forecast for over 15 years.



DS: disconnecting switch
HSVCB: high-speed vacuum circuit-breaker
DCL: direct current reactor
DCLA: direct current line arrester
MC: mechanical contactor
PWM: pulse width modulation

Fig. 4—Circuit Diagram of Regenerative Energy Absorbing Equipment Using Batteries.
A summary of the circuit layout of the developed products is shown.

Product specifications and characteristics

The target product specifications and characteristics of the developed and commercialized regenerative energy absorbing equipment using batteries are listed below:

(1) Rated capacity: 2,000 kW (operates for 15 s in a cycle of 180 s)
(2) Rated voltage: DC 1,500 V/750 V (in the case of 750 V, rated capacity is 1,000 kW)
(3) Switching frequency: 600 Hz (50-Hz regions) or 720 Hz (60-Hz regions)
(4) Lithium-ion batteries: four in series and 20 in parallel

The circuit configuration of the unit is shown in Fig. 4. The unit is configured with a chopper board, a filter board, and a capacitor board. By combining these devices with a DC circuit breaker, it is possible to not only install the unit at established locations but also at optional locations such as close to train stations (where regenerative lapses occur most) and between substations (where electromotive voltage decreases). The chopper device is composed of a multistage chopper that utilizes a 3.3-kV, 1,200-A IGBT (insulated-gate bipolar transistor) element, and staggering the switching phase of four IGBTs in parallel makes four multiple configurations possible, thus reducing ripple current on the feeder side and capacitor side. The lithium-ion rechargeable batteries—used just as in hybrid vehicles—is set up as the standard four in series and 20 in parallel. Furthermore, the operation status of each individual battery, such as charge ratio, is monitored by a battery controller, and that data is transmitted to the chopper device side to enable optimum operation of the each battery. As regards control of the chopper device, the voltages at the start of charge and discharge are altered according to the charge ratio of the lithium batteries, and under the optimum charge range, by means of building in charge and discharge control using the lithium batteries and charge-ratio control for keeping down charge ratio during stand-by time waiting for the next charge (i.e. regenerative power absorption), both constant control of electromotive voltage and control for long battery life can be achieved. This control set up has already been applied to a field test machine, and its effectiveness is being demonstrated under actual operation.

Eco-rectifier

Background to development

As regards track-side-based transformers for DC electric railways, to provide DC to the trains, a silicon

Fig. 5—External View of 6,000-kW Eco-rectifier.
An external view of the eco-rectifier that dispenses with materials which cause global warming is shown.

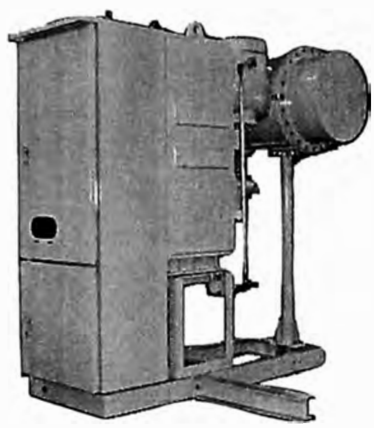


Fig. 6—External View of Dry-air-insulated Switchgear.
An external view of the world's first 72-kV-class dry-air-insulated switchgear is shown.

rectifier is used to convert AC (alternating current) to DC. Up till now, as the cooling medium for the diodes used in the rectifier, PFC (perfluorocarbon) has been used. In the case of the current development, however, aiming to eliminate materials that contribute to global warming, we have developed and commercialized an "eco-rectifier" utilizing heat-pipe cooling with purified water as the cooling medium (see Fig. 5).

Features of product

The main features of the eco-rectifier are listed below:

(1) Elimination of greenhouse gases: for diode cooling, heat-pipe cooling by purified water as the cooling medium is used.
(2) Normal operation even at –20°C: utilizing a VCHP (variable-conductance heat pipe) allows normal operation even at –20°C
(3) Compact design saves space: the installation area for the eco-rectifier is 50% smaller than a conventional one.
(4) Low loss: by using high-voltage diodes, it is possible to reduce the device number by half, thereby reducing loss by 40%.

GASLESS (NO SF_6)-DEVICE

As a way of eliminating the use of SF_6 gas in transformers, implementation of 24-kV C-GIS (cubicle gas-insulated switchgear)[1] is being continued, and dry-air conversion of 72-kV class GIS has recently been completed. Aiming at removal of SF_6 from an SF_6-gas insulating transformer, we have developed a silicone fluid-immersed transformer (using silicon liquid as the insulation medium) and an optical current transformer (which is outstanding in terms of environmental friendliness and reduction of waste materials through its recyclability).

72-kV-class Dry-air-insulated Switchgear

Background to development

Although SF6 gas has extremely good insulating and current-breaker performances in regards to high voltages, it has been designated a greenhouse gas, so its emission into the atmosphere must be reduced drastically. Focusing on high-pressure gas with the same composition as the atmosphere, Hitachi has developed and commercialized the world's first 72-kV-class dry-air-insulated switchgear (see Fig. 6).

As a continuation from the 24-kV class switchgear, we developed this 72-kV class switchgear from the viewpoints of performance as a GIS and as an insulation medium [namely, fundamental characteristics, conversion to a VCB (vacuum circuit breaker) for current cut-off current, switching performance of internal switches, and composite insulation technologies of internal conductors].

Product specifications and characteristics

The main specifications of the 72-kV-class dry-air-insulated switchgear are listed below:

(1) Rated voltage: 72 kV; rated current: 1,200 A
(2) Rated cut-off current: 25 kA
(3) Rated dry-air pressure: 0.45 MPa (VCM compartment); 0.5 MPa (main bus/breaker compartments)

The key features of the GIS are summarized below:

(1) Optimization of a compound insulation structure composed of high-pressure dry air and internal conductors, conductor equipment, and gas storage makes the GIS more compact.

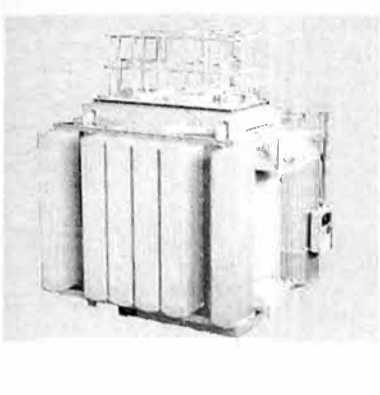


Fig. 7—External View of Silicone Fluid-immersed Transformer.
This transformer can meet the various needs of electrical-power substations for railway use.

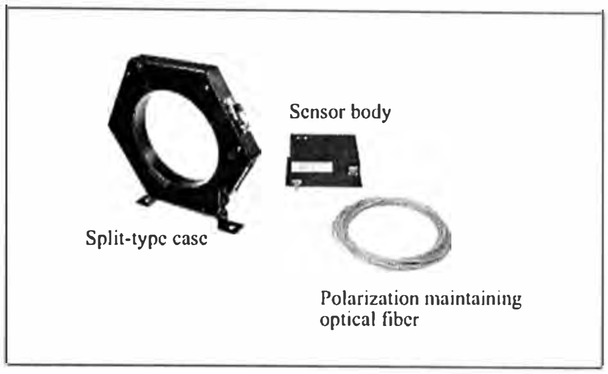


Fig. 8—External View of Optical Current Transformer.
Since optical fiber is used for the sensor part, recyclability is excellent.

(2) A newly developed high-pressure bellows for the VCB part improves reliability.
(3) Separation of the gas compartment from the VCB and other regions, improvement of VCB maintainability and prevention of oxygen deficiency due to non-usage of SF_6 gas, and absence of toxic products owing to the above-mentioned air composition improve the safety of the GIS.

Silicone Fluid-immersed Transformer

Background to development

As regards removal of SF_6 gas from eliminating the use of SF_6 gas from insulated transformers, we focused on silicon fluid, like that successfully used in transformers for compartments of bullet trains, as an alternative insulating material. By carrying out basic research on various properties such as insulating and cooling performance under high voltage, we applied this insulating material and commercialized it in a silicone fluid-immersed transformer that operates up to the very-high-pressure class. Accordingly, we are currently meeting the needs of electric-railway transformers by applying this silicone fluid-immersed transformer (see Fig. 7).

Product and characteristics

The characteristics of silicone fluid-immersed transformer are summarized below:
(1) Since ignition point is above 250°C, fire risk is low, and self-extinguishing nature of the transformer is beneficial regarding accident prevention.
(2) Its non-corrosivity makes its composition stable.
(3) Silicon is the main component, so it can be reduced by hydrolysis back to natural components in an environmentally-friendly fashion.
(4) It can tolerate a large electrical load, so it can be applied as a rectifier for electric railways.

Optical Current Transformer

Background to development

Continuing our research and development on photoelectric sensors (based on the polarization principle by which an electromagnetic field can propagate a photon beam down a fiber), Hitachi has developed and commercialized an optical transformer as a measuring device for DC and AC in railway transformer substations (see Fig. 8). Since the optical transformer uses optical fibers for the sensor parts, its recyclability is good. Moreover, compared with conventional wound-type DC transformers, waste materials produced by upgrading, etc. are significantly reduced.

Product characteristics

The characteristics of the optical current transformer are summarized in the following:
(1) It is lightweight and compact, and directly wrapping the fiber insulation (sensor head) around the measurement target makes it possible to measure current in the target.
(2) Measurement accuracy of DC and AC is ±20 kA and ±10 V at speed of response of 0.5 ms.
(3) Robustness against electromagnetic interference is outstanding, and dynamic range is wide.
(4) Under normal operation, a split-type sensor-head case is used, and the optical fiber is wrapped around the inside of the head.

CONCLUSIONS

In this work, aiming at reducing emissions of greenhouse gases, we have developed transformer substation equipment composed of environmentally-friendly transformer systems. From now onwards, in response to the social demands for more environmental conservation, Hitachi will strive to improve its technologies and develop new railway-use transformer systems in line with the speed of the various social changes.

REFERENCE

(1) N. Kawamura et al., "Latest Railway Substation Systems," *Hitachi Hyoron* **85**, pp. 585-588 (Aug. 2003) in Japanese.

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ANEXO D

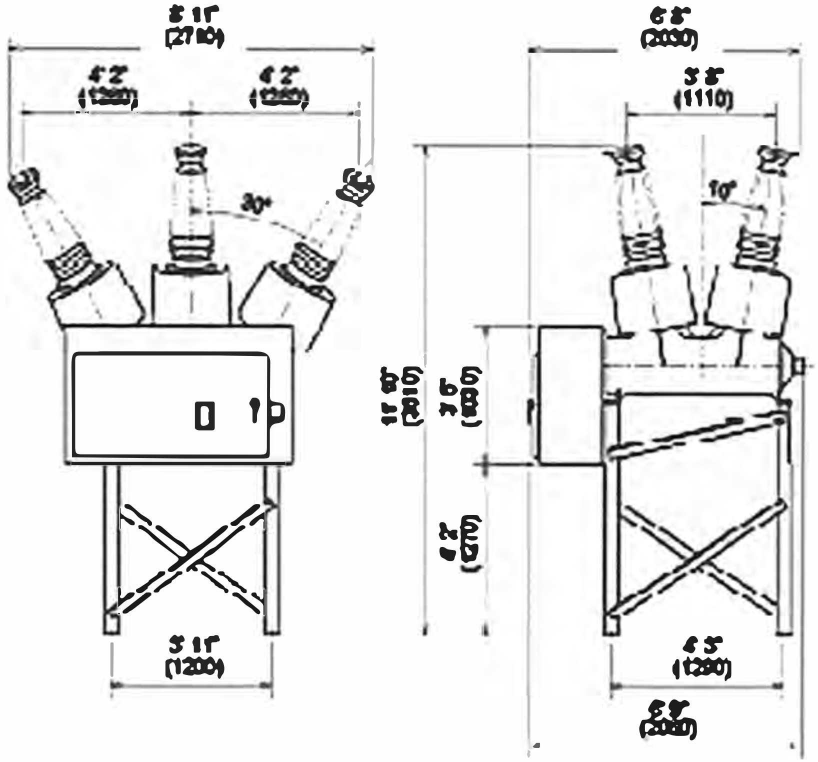
INTERRUPTOR ECOLÓGICO 72.5kV TANQUE MUERTO HVB AE POWER SYSTEMS

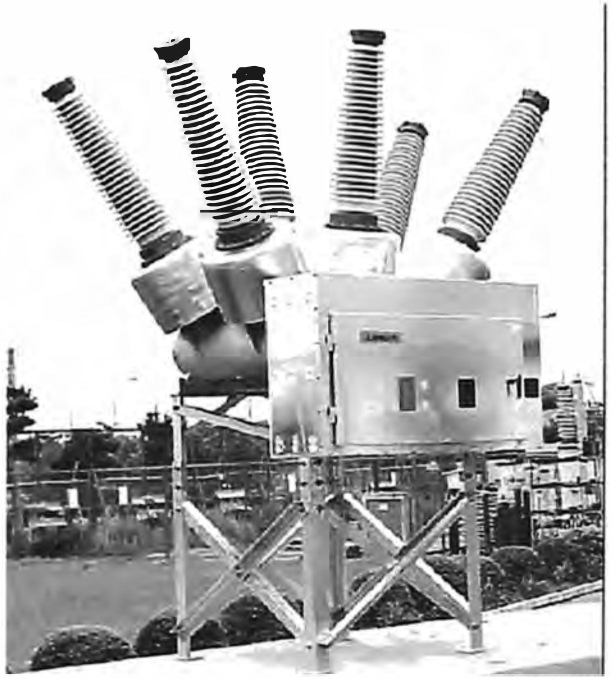
72.5 kV Dry Air Insulated Dead Tank Type VCB

Features

No usage of SF6 gas

Longer life & Easier maintenance than GCB





Rated voltage [kV]	72.5
Rated current [A]	1250/2000
Rated breaking current pkA]	31.5
CB operating mechanism	Motor charged spring
Insulation medium	Compressed air
Rated dry air pressure [psig/Mpa]	72.5/0.5
Applicable standard	ANSI C37.06/IEC

HVB AE Power Systems, Inc.

ANEXO E

INTERRUPTOR EN SF6 145kV TANQUE MUERTO-HVB AE POWER SYSTEMS

HS Series 145kV/40kA/50kA/63kA/2000A-3000A

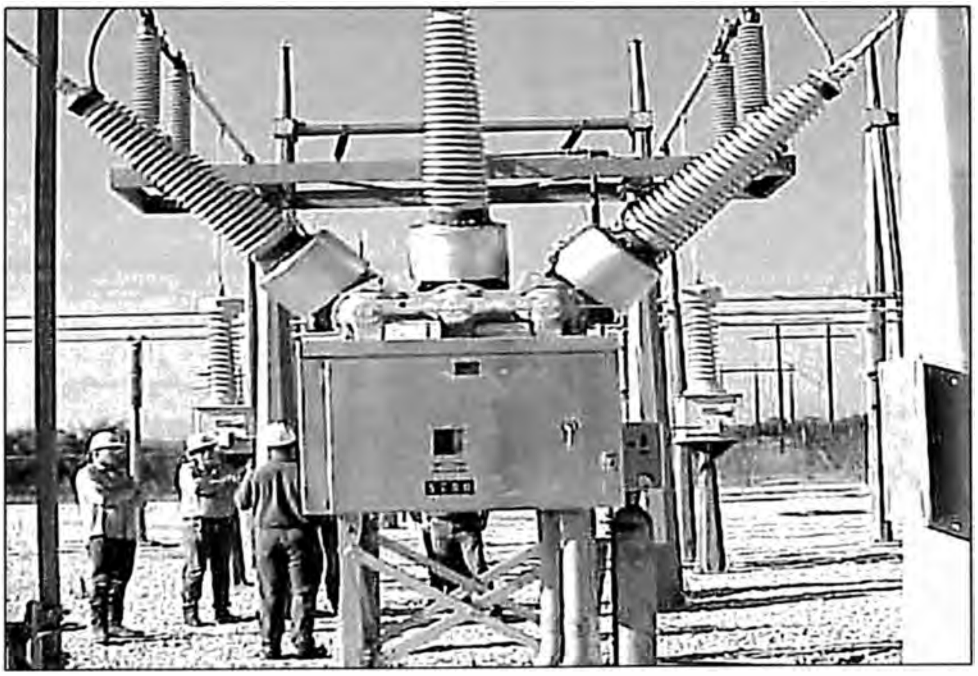
Dead Tank SF_6 Gas Circuit Breakers

HVB AE Power Systems, Inc. 145kV 40kA 2000A – 3000A dead tank circuit breakers have been designed using the vast Engineering and Testing resources as well as the over 50 years of circuit breaker experience of the Hitachi Ltd. Corporation in Hitachi City Japan. The circuit breaker design philosophy has been to provide the shortest installation time, lowest maintenance needs and highest reliability in the industry. This is evident from the beginning of the project, through type testing and into production

We have achieved this through an evolution of our industry leading GIS (Gas Insulated Substation) Mechanism and Interrupter design. The spring-operated mechanism has been designed to provide a consistent 3 cycle interrupting time, predictable operation and minimal required maintenance. The Interrupter is designed to the same rigorous standards as our other breaker ratings. These standards include a true puffer interruption and less than 0.5% annual SF6 gas leak rate. The HS Series 145kC breaker continues our reputation for ease of maintenance provided by access to the puffer cylinder and contacts through the inspection port without the time consuming procedure of removing the interrupter.

In addition to meeting or exceeding all ANSI and IEC circuit breaker standards, we also focused on making this design more installation and maintenance friendly. The breaker will ship with the bushings installed and positive pressure gas. These advantages will allow you, the customer, to install the breaker in less time, with fewer personnel and with no specialized equipment for gas filling.

The HVB AE Power Systems, Inc. 145kV HS gang operated breaker provides the industry's best solution for HV applications where short installation time, exemplary long-term reliability and reduced lifetime cost of ownership are involved in the evaluation process.



FEATURES AND BENEFITS

- **Aluminum Tank Design Benefits**

  Aluminum construction allows for a lighter breaker.

  No painted surfaces which could rust.

  Applicable to extreme environment

- **Lower Installation Costs**

  This breaker ships with the bushings installed and positive pressure SF6 gas. There is no need to perform an internal inspection or pull vacuum, just Charge with SF6 gas and connect interphase wiring.

  No at site wiring connections.

  Reduced weight and foundation size needed.

- **Low Cost of Ownership**

  Maintenance advantage with access ports allows inspection and/or parts replacement without dis-assembling the breaker

- **Tested Performance and Reliability**

  Rigorous type tests of 10,000 mechanical operations, our standard

  Breakers carry 90% short line fault rating

  Isolated Phase Interrupting eliminates the possibility of a single-phase fault affecting the security of all phases

  High Residual Dielectric Strength

  O-0.3-CO rated duty cycle

  Rated current carrying capability at atmosphere pressure SF6 and full rated interrupting ability at lockout pressure

- **High Performance at Low Temperatures**

  Normal operation to -30° C without the need for electric heaters

  Designs Available for reliable operation at temperatures as low as -50° C

- **Mechanism Features**

  Motor charged close spring.

  Universal type spring charging motor can operate VAC or VAC.

  A transfer switch is optional which allows the source to change in the event of the loss of AC

  Quiet Operation

- **World Class Breaker Design**

  All breakers have rupture disk SF6 release

  Three creep

  Porcelain bushings are standard with composite available

- **Interrupter Features**

  Only SF6 for open gap insulation

  No insulation between open contacts

  Low operation pressure (85 psig)

	145 kV 40kA	145 kV 50/63kA
Voltage	145	145
BIL (kV crest)	650	900
60 Hz withstand (kV)	310	425
Continuous Current	2000/3000	4000
Interrupting Current	40kA	50/63kA
Interrupting time	3 cycle	3 cycle

HVB AE Power Systems, Inc.
7250 McGinnis Ferry Road
Suwanee, GA 30024

For additional information on the HS Series 145kV contact HVB AE Power Systems, Inc. at 770-495-1755

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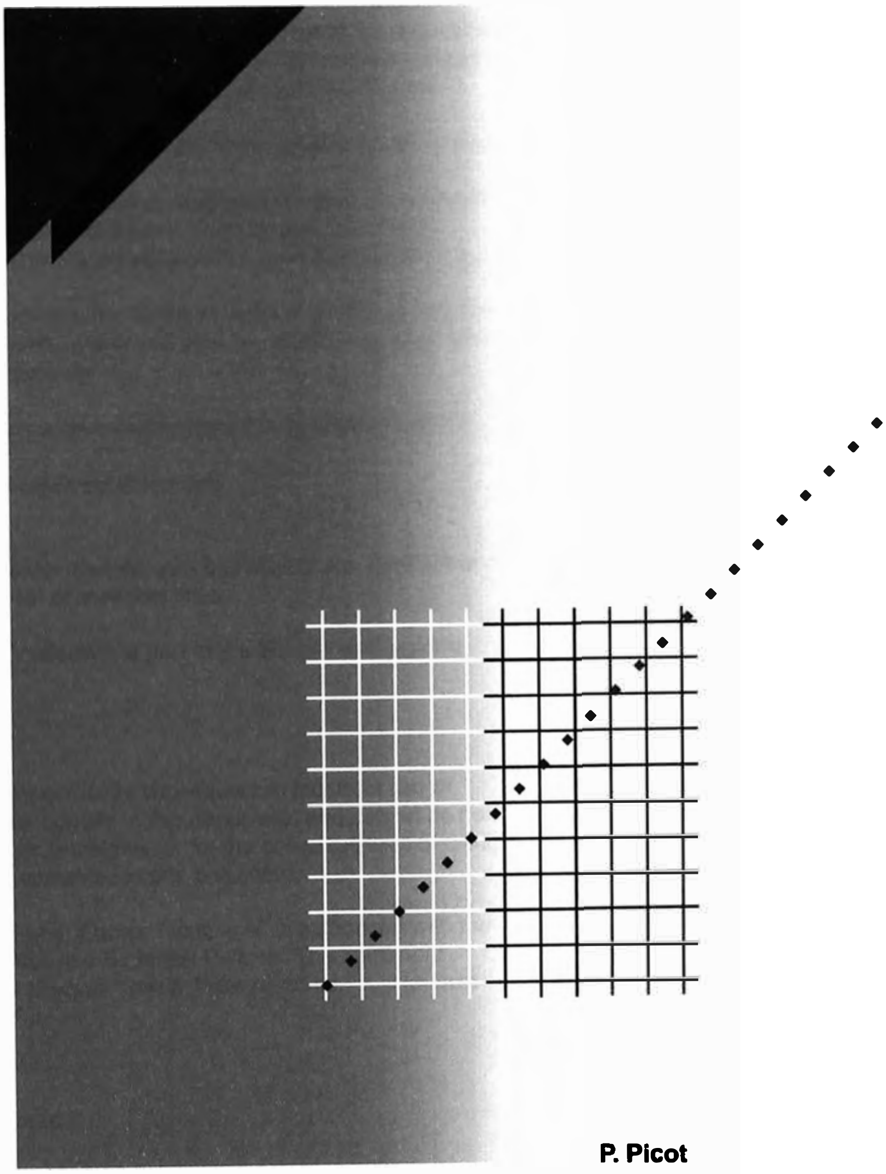
ANEXO F

INTERRUPTORES DE VACÍO-SCHENEIDER

Cahier technique no. 198

Vacuum switching



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no. 198

Vacuum switching

Philippe PICOT

Ingénieur civil des mines (ENSMP)
Hired in 1982 by Merlin Gerin, he has held different positions, primarily in the technical field of the Medium Voltage division.
Since 1995, he has been participating in the development of Schneider-Electric's vacuum interrupter range.
He is presently in charge of technological anticipation of MV switchgear.

ECT 198 first issue, March 2000

Vacuum switching

This "Cahier Technique" constitutes a general presentation of basic notions relative to the functioning and use of vacuum switching devices.

The first section, entitled Theory and Use of vacuum switching, is a brief description of the physical phenomena that are associated with vacuum switching, and of their use. It also includes a presentation of the different technological options that are available to vacuum interrupter designers.

The second section is dedicated to the interaction between vacuum switching devices and the electrical network, in inductive circuits for which vacuum switching may cause overvoltages, and to overvoltage protection means.

In the third section, the author explains how vacuum switching characteristics, which have been presented in the two preceding sections, determine the application fields best suited to this technique, depending on voltage levels and switchgear types.

This "Cahier Technique" is completed with an extensive bibliography of works and other documents which the reader can consult if he wishes to acquire more in-depth information on a particular point.

Contents

1 Introduction: use of vacuum as a breaking medium in the electrical switchgear industry

SF6 and vacuum are the two most modern breaking techniques in the fields of Medium Voltage (from 1 to 52 kV) and High Voltage (> 72.5 kV). They appeared in the 1960's and rapidly developed as of the 1970's. Today they have replaced the former air and oil breaking techniques (see fig. 1).

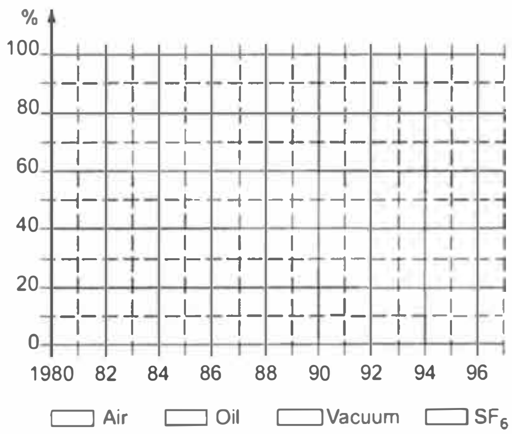


Fig. 1: evolution of MV circuit-breaker markets in Europe.

Whereas SF6 is used in all of the medium voltage and high voltage ranges, vacuum has primarily developed in the medium voltage field, with limited incursions in low voltage and in high voltage: the two techniques only compete with each other in the medium voltage field.

This notion of rivalry between the two techniques is now in fact out of date: even if at some time there was commercial competition between manufacturers that opted for one or the other of these techniques, today all large-scale manufacturers offer both techniques so as to be able to satisfy as best as possible their client's needs. Indeed, each technique has its strong points and its weak points. Even if each is highly multi-functional and can offer a reliable and competitive solution for most medium voltage interruption problems, users want to be able to choose for themselves in function of their applications, operation and maintenance policies, priorities ... and of course habits!

In the past, the vacuum switching technique was first developed by American and English manufacturers (the pioneers were General Electric and VIL), followed by the Japanese and the Germans: these countries have the common feature of using networks with relatively low voltage ratings (from 7.2 to 15 kV) for medium voltage electrical energy distribution. However, in countries like France and Italy which distribute electricity with voltage levels near 24 kV, manufacturers opted for the SF6 breaking technique.

It is remarkable to note, 30 years later, the appropriateness of these technological choices in regard to the foreseen application. In fact still today, a global technical-financial evaluation of both techniques shows an equivalence when using voltages between 12 and 24 kV, with a relative advantage for SF6 above this voltage level, and for vacuum below this level. However, the difference in cost remains low, which explains how the two offers, vacuum and SF6, can coexist, for all medium voltage levels from 7.2 to 36 kV.

2 Theory and use of vacuum switching

2.1 The dielectric properties of vacuum

Any breaking medium must first be a good insulator for it is to stop current from flowing through it. Vacuum is not an exception to the rule: it has interesting yet particular dielectric properties in comparison to other insulating gases that are commonly used under pressure that is higher than or equal to 1 bar.

Vacuum, that is qualified as being "high" (pressure range from 10^{-1} to 10^{-5} Pa, i.e. 10^{-3} to 10^{-7} mbar) of vacuum switch interrupters (see **fig. 2**) is in fact a low pressure gas: typically 10^{-6} mbar in a new interrupter.

Fig. 2: a 17.5 kV vacuum interrupter by Schneider Electric.

At this pressure, a 1 mm^3 volume still contains 27.10^6 gas molecules, but their interactions are negligible since their mean free path between two collisions is of the order of a hundred meters: the term "vacuum" is thus appropriate since each molecule behaves as if it were practically alone.

Reminder concerning the dielectric behaviour of gases

At normal pressure levels (atmospheric pressure and above) the dielectric behaviour of gases is represented by the right branch of the Paschen curve (see **fig. 3**): the breakdown voltage V is a growing function of the p d product (**p** = pressure, **d** = distance between the electrodes). This relation characterises the chain ionisation mechanism (Townsend avalanche effect) responsible for the breakdown: the electrons must acquire between two collisions sufficient energy (proportional to $\frac{V}{p\,d}$) to ionise the gas molecules and thus create other electrons.

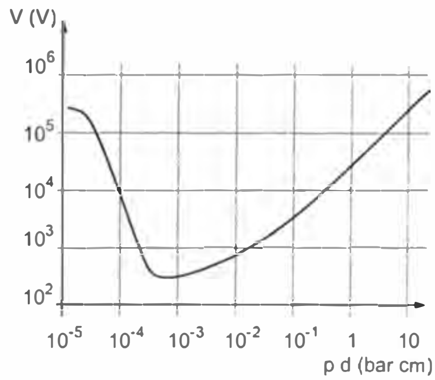


Fig. 3: change in dielectric strength of the air in function of the pressure (Paschen curve)

At low pressure values, this mechanism no longer functions. In fact, the electrons can acquire a lot of energy during their mean free path, but the probability that they encounter molecules to be ionised before reaching the electrode becomes weak: the electron avalanche and multiplication process of the charged particles cannot take place and the dielectric withstand is improved. This is what the Paschen curve shows: a minimum dielectric withstand for a p d product in the region of 1 Pa m for nitrogen. Below this value, the dielectric withstand rapidly improves (left branch of the Paschen curve) up to a level of values for p d that are lower than 10^{-2} Pa m. This level characterises the dielectric behaviour in vacuum interrupters (pressure lower than 10^{-3} mbar, i.e. 10^{-1} Pa, distances in the region of 1 to 10 cm). It corresponds to a high withstand level that is comparable to that of SF6 gas which is at roughly 2 bars for intervals in the region of one cm. In this field, it is no longer the residual gas ionisation mechanisms that limit the dielectric withstand but rather phenomena linked to the surface condition of electrodes, such as field electron emission and the presence of detachable particles.

c Field emission

Electron emission consists in extracting electrons from the metal of electrodes. This can be done by sufficiently raising the temperature of the metal: it's the thermionic emission that is produced at the heated cathode level of the electron tubes. Another means is to apply a sufficiently strong electric field to the metal surface. This last phenomenon, field emission, is likely to be encountered in vacuum interrupters. It is controlled by the Fowler-Nordheim equation that, in a simplified form, is written:

$$j_e = \frac{AE^2}{\phi} \exp\left(-\frac{B\,\phi^{1.5}}{E}\right), \text{ where}$$

j_e is the electronic current density in Am^{-2}
$A = 1.54 \times 10^{-6}\ AJV^{-2}$
E is the electric field in Vm^{-1}
ϕ is the work function in eV (4.5 eV for copper)
$B = 6.83 \times 10^{9}\ VJ^{-1.5}\ m^{-1}$
As can be seen from the values indicated above, field emission only becomes appreciable for field values on the surface of metals that are included between a few $10^9\ Vm^{-1}$ and $10^{10}\ Vm^{-1}$.
Very high values are being dealt with here; values that are significantly higher than the macroscopic field values for typical vacuum interrupters (in the region of $10^7\ Vm^{-1}$ = 100 kV/cm). Even so field emission has been acknowledged in vacuum interrupters: it must therefore be concluded that locally, at the microscopic site level, the electric field is reinforced by an enhancement factor β in the region of a few 10^2 or 10^3. The phenomena that could explain these high β values have not yet been completely elucidated by researchers, who in general favour the microscopic point effect, or the inclusion of insulating particles at the surface of metals.

v Voltage conditioning
The existence of active microscopic emission sites in general results in poor dielectric withstand of new interrupters (a few 10 kV/cm); however, it has been experimentally noted that repeated dielectric breakdowns destroy these sites or at least considerably reduce the value of the enhancement factor that characterises them. A satisfactory dielectric withstand (in regard to assigned values) can thus be obtained only once the voltage conditioning process has been completed. It consists in applying a high voltage (around the expected withstand value) for a few minutes: the multiple breakdowns that occur, progressively raise the withstand between electrodes. This phenomenon is illustrated in **figure 4** which shows the change over time of the breakdown voltage as discharges pass: an upper limit for dielectric withstand improvement appears near $10^8\ Vm^{-1}$, which again corresponds to an "irreducible" microscopic β of about 100.

v Breakdown mechanisms
Dielectric breakdowns that originate in electronic current emission implement additional mechanisms: in fact, stable electronic currents (for maximum values of a few mA) do not

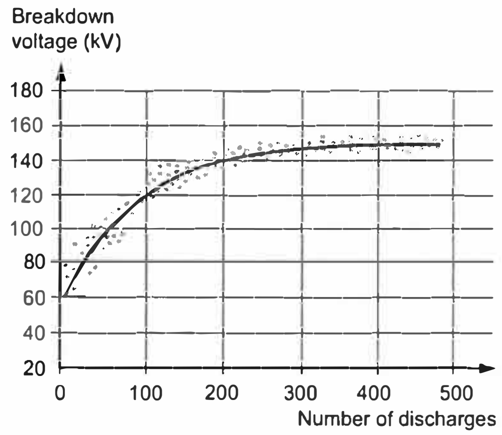


Fig. 4: improvement of the breakdown voltage between two electrodes in vacuum as a function of the number of discharges.

necessarily degenerate into a breakdown if the applied voltage is not increased, they may even diminish by themselves through the conditioning effect. Breakdown, itself, is linked to the creation of localised plasma (ionised gas), which is sufficiently dense for the electron avalanche phenomenon characteristic of gaseous discharges to be produced.
The plasma may be produced on the cathode side through the explosion of the microscopic emissive site caused by the intense overheating due to the current density which is locally very high (Joule effect): breakdown is produced in the metal vapour that was generated by the destruction of the emissive site.
The plasma may also be produced on the anode side which is bombarded by a beam of highly energetic electrons (which also results in the emission of X-rays). This localised flow of energy causes the desorption of gases absorbed on the surface and the vaporisation of anode metal: the gas produced from this is thus ionised by beam electrons, and the breakdown occurs.

c The influence of detachable particles
A second factor is likely to cause dielectric breakdowns in vacuum: detachable particles present on the surface of the vacuum interrupter walls. Set free, either by a shock, or by the effect of electrostatic forces, these charged particles acquire energy by going through the inter-electrode gap. At the moment when they impact with an electrode that attracts them, they are likely to trigger a breakdown in two ways, which may be complementary:
v through a local rise in the gas density due to the desorption of absorbed gas molecules;
v by triggering the field emission phenomenon and the partial vaporisation of the particle or of the electrode under the effect of the beam that bombards them.

Confirmation of the practical importance of the particles is the experimental observation that the dielectric withstand in vacuum between two electrodes increases approximately in proportion to the square root of the distance which separates them. This relation can be explained by the hypothesis that the particles must reach sufficient energy (proportional to V^2/d) to be able to cause a breakdown. For this same reason, large particles, that can carry a higher electrical charge, are more troublesome than small ones.

From the unfavourable influence that detachable particles have on the dielectric withstand of vacuum interrupters, two consequences are to be noted:

c it is difficult to reach very high withstands, even with a great amount of space between electrodes (see **fig. 5**),

c the dielectric withstand of a vacuum interrupter presents a random character: a delayed breakdown can occur in regard to voltage application and for a voltage of less than that which was tolerated right before without a breakdown.

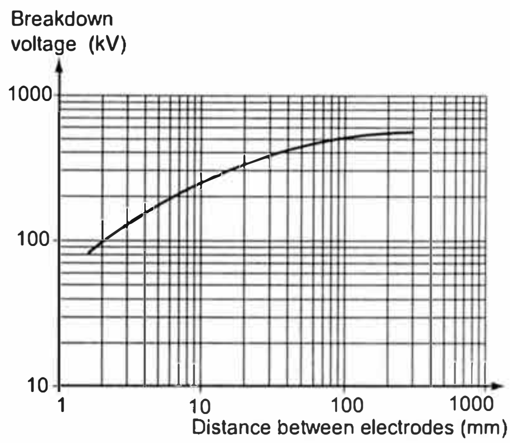


Fig. 5: accessible withstands for very large distances between electrodes.

Resume

c Vacuum shows interesting dielectric properties if applied voltages are limited to a region of 100 to 200 kV, which corresponds to an insulation level required for voltage ratings of i 36 kV for which distances of a few centimetres between electrodes suffice. Above this level, reaching the necessary dielectric withstand level becomes laborious and less efficient than with SF6 gas insulation.

c The dielectric withstand of a vacuum switching device evolves over time. Indeed, mechanical operations and the effect of electrical arcing modify the contact surface condition and generate particles: the withstand level reached after voltage conditioning therefore cannot be considered as permanently acquired. Vacuum is thus not the ideal insulating medium when the reliability of dielectric withstand is essential, for example for a disconnector application.

2.2 Electrical arcing in vacuum

Even though, as described in the above section, vacuum may be an excellent dielectric, an arc can very well "live" in the "vacuum". In fact, the arc voltages in vacuum are in general considerably lower than those of arcs that develop in other mediums, which constitutes an advantage in regard to the energy that is dissipated in the arc. Arcs in vacuum occur, by voluntarily simplifying, in two main forms: the diffuse mode and the constricted mode.

A diffuse mode, characteristic of the "vacuum" medium

The diffuse mode is specific to arcing under vacuum: it shows remarkable particularities which clearly differentiate it from arcings in gaseous mediums. It is the mode which a vacuum arc naturally adopts for a current range covering a few amps to a few kA.

The main characteristics of the diffuse mode are as follows:

c the cathode emits into the inter-electrode gap, via one or several cathode spots, a globally neutral plasma made up of electrons and of high speed ions whose velocity is primarily directed perpendicularly to the surface of the cathode;

c the anode, with its entire surface immersed by this plasma, reacts as a passive charge collector.

The cathode spots and the plasma are specificities of the arc in the diffuse mode.

c The cathode spot

The cathode spot is a very small sized zone (radius in the region of 5 to 10 µm), capable of emitting a current that can reach some hundred amps.

Extreme temperature and electric field conditions rule at the cathode spot level (typically 5000 K and 5 10^9 V/m). These conditions allow for electronic emission by combining thermionic and field emission mechanisms into thermo-field emission which is capable of producing very high current densities (between 10^{11} to 10^{12} A/m^2).

Above 100 A, this spot subdivides itself and several spots coexist on the cathode, in sufficient number to transit the current at the rate of some hundred amps each. They mutually drive each other back, which led their movement to be qualified as "retrograde" for it is contradictory to the normal effect of electromagnetic forces. Thus arcing in the diffuse mode tends to occupy the entire available surface on the cathode (even if at any given moment the emissive sites only represent a very small fraction of the cathode).

c The plasma

At the macroscopic level, the cathode spot (crater and close-range plasma that is associated with it) seems to be the production point of a low density plasma coming from the spot and which fills the inter-electrode gap. This globally neutral plasma (equal densities of + and - charges), is made up of electrons and ions which are typically double charged (for arcing on electrodes with a Cu base). One of the characteristics of this plasma is the great speed of the ions which have an energy that is higher than the arc voltage (which testifies to the highly energetic phenomena that are produced in the zone of the cathode spot). It is therefore not difficult for these ions, which emanate from the spot with a distribution of speed approximately in cos (angle/normal) to reach the anode and create an ionic current in the opposite direction to the main electronic current which typically represents 10 % of the arc current. The directed velocity of these ions is in the region of 10^4 m/s, higher than their thermal agitation speed.

One of the significant consequences of the high speed of the ions created by the cathode spots is their low transit time through the inter-electrode gap (typically in the region of 1 μs).

The plasma, created by a cathode spot, is made up of highly mobile particles (rapid electrons and ions, virtually no neutral particles) and thus disappears very rapidly when the spot stops functioning (around current zero).

The anode is immersed in the plasma that emanates from the cathode spots. It behaves like a passive electrode that collects charges and extracts the current that is imposed by the circuit by adjusting its voltage: it is negative with respect to the plasma as long as the current is lower than the one that corresponds to the impacts linked to the thermal agitation of electrons.

The distribution of voltages in the arc is as follows:

v a cathode voltage drop in the region of 20 V in the immediate area of the cathode;

v a voltage drop of a few volts in the plasma which increases with the distance and the current (positive characteristic allowing for the coexistence of several parallel arcs, contrary to arcs in gas);

v a negative anode drop in the case considered above (moderate current absorbed by the anode).

In this mode, there is little cathode erosion: it corresponds to the ion flow leaving the cathode, i.e. roughly 40 μg/C. A significant number of these ions place themselves on the anode which, in alternating current, means that net erosion is much lower: approximately divided by a factor of 10 for contactors that operate in this mode with limited currents and electrodes with little spacing.

A constricted mode similar to the one of an arc in a gaseous medium

When the current increases, the previously described situation tends to evolve first of all on the anode side. Several phenomena converge towards this evolution.

c First a contraction of the plasma column generally explained by the Hall effect (charge deviation by the azimuthal magnetic field created by the other current lines, from which the appearance of a radial component tends to confine the current lines towards the axis): the current is concentrated on a more limited area of the anode.

c Furthermore the anode attracts more and more electrons, and the neutrality of the plasma is no longer ensured: positive ions are lacking to balance the space charge of electrons near the anode. This leads to the formation of a positive anode voltage drop which is needed to attract electrons despite the space charge. The energy received by the anode increases and tends to be concentrated on a reduced area: the anode heats up and starts to emit neutral particles that are ionised by the incident electrons. Near the anode, a secondary plasma, made up of secondary electrons and ions that are less energetic than those emitted by the cathode spots, appears.

These phenomena result in the appearance of a luminous anode spot, considerably larger (in the region of a cm^2) than the cathode spots, made of molton metal which spills considerable amounts of vapour, which becomes ionised in the flow coming from the cathode, into the inter-electrode gap.

This contraction effect on the anode side also leads to a contraction on the cathode side since a preferential path is created thanks to the plasma generated by the anode: a cathode spot corresponding to the anode spot is established and the arc takes up the constricted mode that is characteristic of arcs in a gaseous medium. Here, we are dealing with an arc in an atmosphere of dense metallic vapours, for which operating mechanisms now rely on the ionisation of the gaseous medium.

This arc in the constricted mode is thus characterised by a plasma made up of electrons (most of which are secondary), of neutral particles and ions the energy of which is near that of the neutral particles, thus relatively slow.

.3 Phenomena associated with breaking at current zero

General breaking principles

All medium voltage circuit-breakers take advantage of the natural passage of alternating current through zero (twice per period, i.e. every 10 ms for a 50 Hz current) to interrupt the current.

c The inevitable arc phase
Once a fault current has been established in a circuit, the separation of circuit-breaker contacts does not have an immediate repercussion on current flow. At the level of the last contact points, the current density becomes very high, which causes a local fusion and the appearance of a liquid metal bridge. The contacts continue to move away from each other, this bridge is heated up by the current and becomes unstable and its rupture results in the appearance of a constricted arc in the metal vapours originating from the liquid bridge explosion. The arc voltage that appears is, in the case of a vacuum, low in comparison to the electromotive forces of LV or HV network generators: the current flowing in the circuit is thus not considerably affected, nor limited, by this arc voltage.

This arc will adopt the diffuse mode or the constricted mode described in the preceding section, possibly evolve from one to the other, and will be maintained up to current zero.

c The recovery phase after current zero
If the plasma, which up to now allowed for the current to flow through, takes advantage of this break to dissipate itself very rapidly, the current may be prevented from establishing itself for the following half-cycle. A transient recovery voltage (TRV), imposed by the circuit, then appears at the terminals of the element that has switched from a conductive state to an insulating state. In the case of a short-circuit, this TRV is caused by the oscillations between the local capacitances and the network inductances. In its initial phase, it approximately presents a (1-cosinus) shape with a natural frequency in the order of a few tens of kHz in MV network and reaches a peak value that is greater than the normal network voltage, which corresponds to average rates of rise of a few kV/µs.
If the newly insulating medium tolerates the dielectric stress which is then applied to it, the current is successfully interrupted (see **fig. 6**).

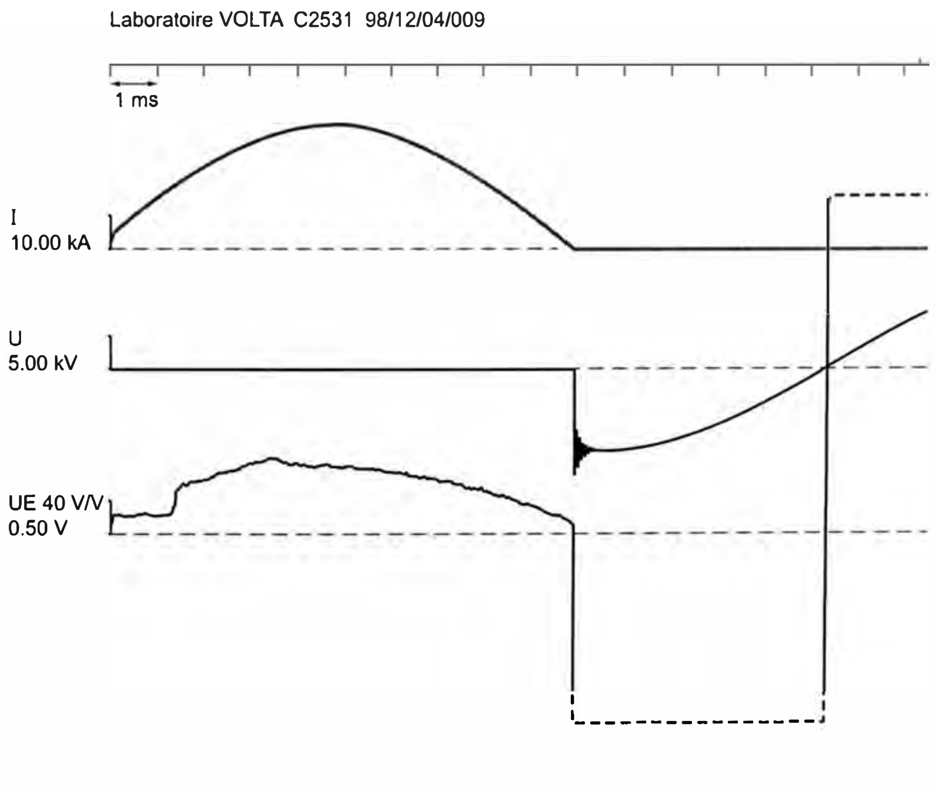


Fig. 6: a successful current interruption (source Merlin Gerin).

Case of vacuum switching

To determine the conditions for successful current interruption, it is necessary to study the phenomena that intervene near current zero in the vacuum arc plasma.

c Post-arc current
Near the end of the half-cycle, the current decreases at a rate which is proportional to the peak current value and to network frequency (di/dt = ω Î). The vacuum arc returns to the diffuse mode and, near current zero, only a single cathode spot remains. However, the inter-contact gap is still filled with a residual, globally neutral plasma, that is made up of electrons, ions and neutral particles which come from the preceding arc.

At the time of current zero, the last cathode spot extinguishes itself because the arc voltage disappears. Thus, the emissive site, which created charged particles (electrons and ions) needed to transport the electric current, no longer exists.

From this moment on, a voltage with an inverse polarity to that of the preceding arc voltage (the TRV), starts to appear between the two contacts: the ex-anode becomes negative in regard to the ex-cathode and drives back the electrons. The current that flows in the circuit is now only made up of ionic current that the ex-anode extracts from the residual plasma that becomes scarce: this current with an inverse polarity to that of the arc current is called post-arc current.

The ex-anode is thus no longer in contact with the neutral plasma which is still present in the inter-contact gap: it is separated from it by a sheath from which the electrons, driven back by the negative voltage of the ex-anode, are absent. Only positive ions cross the neutral plasma boarder into the sheath and are then accelerated towards the ex-anode. The voltage that appears between the ex-cathode and the ex-anode is thus applied only to the thickness of the sheath that separates the neutral plasma from the ex-anode. Moreover, the presence of positive space charges in this sheath reinforces the electric field on the surface of the ex-anode which is higher than the average field that corresponds to the TRV value divided by the sheath thickness (see fig. **7**).

The thickness of the sheath that surrounds the ex-anode is proportional to the voltage applied between the neutral plasma and the electrode and inversely proportional to the density of the positive ions: it thus increases according to the change in TRV and all the more rapidly as the plasma rarefies. When the limit of the sheath reaches the ex-cathode, the residual plasma has disappeared, since all of its charges have

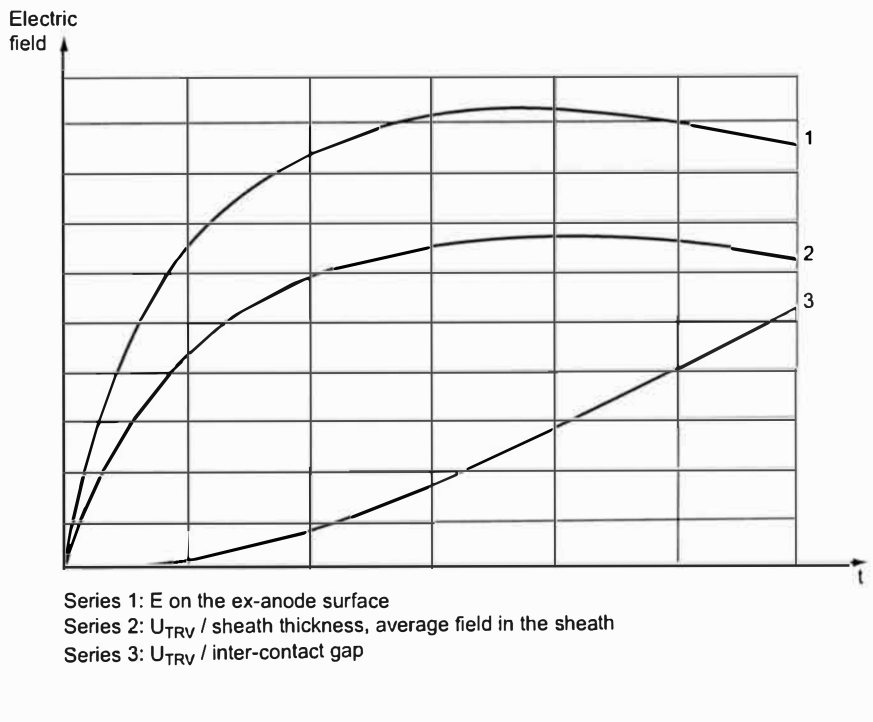


***Fig. 7:** electric field on the surface of the ex-anode and the corresponding average field between the electrodes.*

been used by the post-arc current which becomes nil.

These phenomena take place on a very reduced time scale: the total length of post-arc current is typically 1 to 10 µs (see **fig. 8**).

c Causes of interruption failure

So that current can be maintained, mechanisms that create electrical charges must replace the cathode spots that have extinguished on the ex-cathode.

The first possible mechanism is the ionisation of the neutral metal vapour that is present in the inter-contact gap. This ionisation is all the more easy that the density of neutral particles is higher. If the vapour density is very high (very hot zones on the contacts produce a great amount of metal vapours), the current does not interrupt at all: there is no increase in the TRV, this is called "thermal non-breaking".

If the density of neutral particles is sufficiently high so that the dielectric withstand of the vacuum can be reduced (approaching the minimum value of the PASCHEN curve), the current can be interrupted, but the inter-contact gap cannot tolerate the applied TRV and a breakdown occurs during the rise in the TRV, here we have "dielectric non-breaking".

A second possible mechanism is the appearance of cathode spots on the ex-anode. For this, electronic emission conditions must be locally reunited on the surface of the ex-anode:

v thermionic emission if very hot points remain, this is the case when the anode contains refractory metal (W);

v field emission or combined T.F. emission if the electrical field applied to the surface is significant at certain sites with a high enhancement factor β.

We previously saw that the electric field applied to the surface of the ex-anode appears with high values as of the start of TRV application since the sheath is thin; the higher the ion density, the thinner the sheath is. Furthermore, the ex-anode is bombarded by ions that have been accelerated in the sheath by the TRV, which causes localised overheating. The probability of cathode spots appearing on the ex-anode is thus greater if the density of ions in the residual plasma is high, which goes hand in hand with a high density of neutral particles which slow down, through collision, the rapid ions emitted by the cathode spots, thermalize them (average energy near the temperature of the plasma) and slow their diffusion at the time of current zero.

If plasma density is sufficiently low at the time of current zero, the conditions for successful breaking have probably been satisfied: the current is interrupted and the inter-contact gap withstands the recovery voltage up to its peak value.

In the case of vacuum circuit-breakers, success is not however entirely guaranteed once this stage has been completed. In fact, for a few

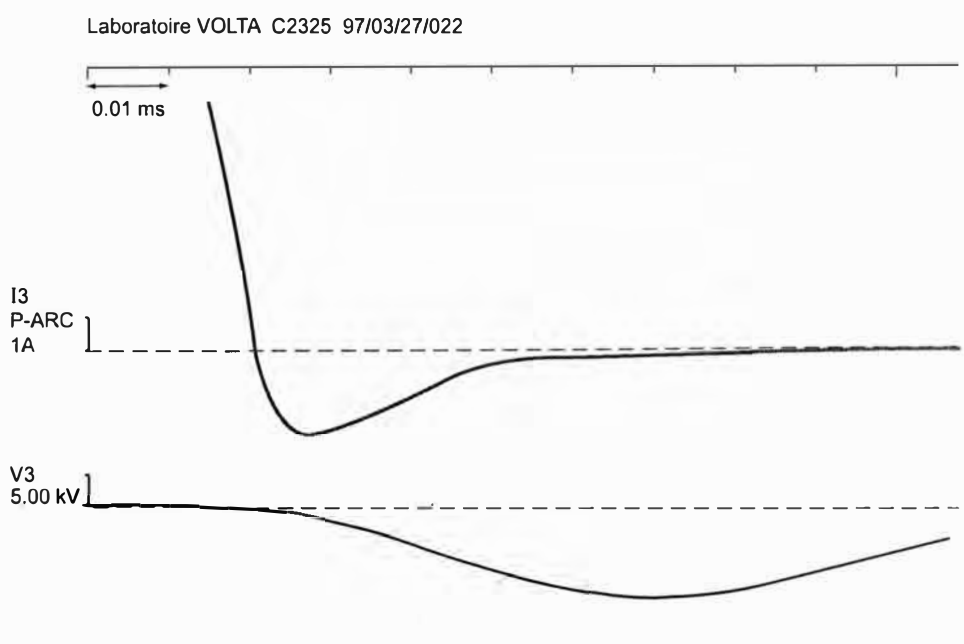


Fig. 8: post-arc current with a particularly long length of roughly 40 µs, test at the breaking capacity limit of the interrupter.

milliseconds after the break, the situation inside the interrupter can still change and dielectric breakdowns can occur:

v particles generated during the arcing phase can detach themselves from the walls under the effect of vibrations and/or electrostatic forces;

v molten areas on contacts can emit droplets under the effect of electrostatic forces;

v solidification of the liquid metal can modify the surface of the contact or free dissolved gas.

When a vacuum interrupter is tested at the limit of its breaking capacity, after breaking that appears to be successful, it is not rare to see late occurring dielectric breakdowns (see **fig. 9**) which may be:

v either transient (duration of a few μs) for the interrupter is able to break the HF current that follows the discharge. If these transient breakdowns occur more than a quarter of the industrial frequency period after current zero, they are considered as non-sustained disruptive discharges (NSDD) and interpreted as a sign of device weakness (for this reason the maximum number of NSDD that is tolerated is three for a complete series of breaking tests on a circuit-breaker as in IEC 60056);

v or complete and, in this case, the power current reappears after a more or less long interruption period (in the region of 0.1 to 1 ms).

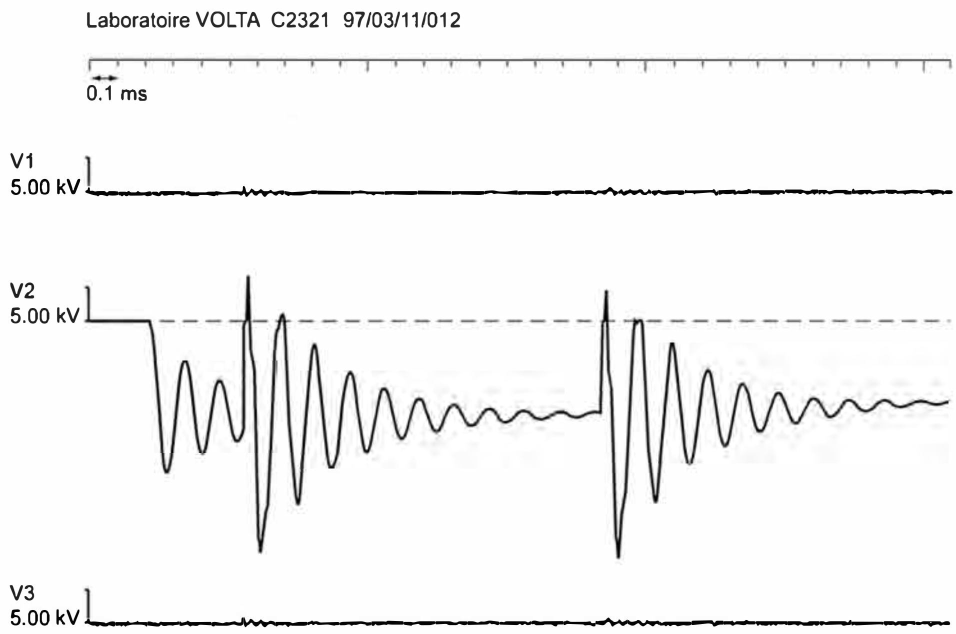


Fig. 9: example of late occurring dielectric breakdowns.

2.4 The practical design of vacuum interrupters

Choice of the breaking technique

The preceding section highlighted the conditions that must be satisfied for successful breaking. These conditions are almost always satisfied when an arc remains in the diffuse mode, that is to say when currents to be interrupted do not exceed a few kA. It is the case for switches and contactors that can therefore use very simple butt contacts.

When an arc passes into the constricted mode, the energy is dissipated onto a reduced electrode surface, and it causes localised overheating and considerable vaporisation. If this arc remains immobile, breaking is no longer guaranteed.

Two methods are used to overcome the difficulties that are produced by the passage of an arc into the constricted mode.

v The first consists in causing a rapid circular movement of the constricted arc so that the energy is distributed onto a large part of the contact and overheating is limited at all points: this is obtained through the application of a radial magnetic field $\vec{Br}$ in the arc zone.

v The second consists in preventing the passage into the constricted mode through the application of an axial magnetic field: when the field reaches a sufficient value, the arc is stabilised in a mode qualified as a diffuse column and does not concentrate itself ; even though it is immobile the arc uses most of the contacts' surface and overheating therefore remains limited in this case as well.

c Radial magnetic field technique $\vec{Br}$

The constricted arc can be compared to a conductor through which a current flows, the direction of which is parallel to the axis of the contacts. If a radial magnetic field (RMF) is applied to this conductor, the resulting electromagnetic force will have an azimuthal direction and cause rotation of the arc around the axis of the contacts.

The $\vec{Br}$ field is caused by the path imposed on the current in the contacts. Two types of contact structures are used to obtain this result (see **fig. 10**):

v contacts of the spiral type,

v contacts of the "cup" or "contrate" type.

Correct functioning of RMF interrupters is linked to obtaining a satisfactory compromise at the contact geometry level and in particular of the slot width for contacts of the spiral type:

v if the width is too large, the arc has a hard time "jumping" from one part of the contact to the other, which may make it stationary at the end of the track and thus overheat part of the contact (since the arc is in the constricted mode);

v if the width is too small, the slot may be easily filled by the fusion of contact material, and the current path, thus modified, leads to the disappearance of the RMF and immobilisation of the arc.

Even though mobile, the rotating arc remains constricted and therefore exerts energetic force on the part of the electrode which carries it, the high pressure of the arcs roots expulses the molton contact material in the form of droplets. This process is an efficient means of limiting the overheating of the rest of the electrode (or to facilitate its cooling), for the energy brought by the arc is taken away with the expulsed material which has condensed on the surrounding walls; in return, it leads to relatively high contact erosion.

c Axial magnetic field technique $\vec{Ba}$

When an arc plasma is submitted to a sufficient axial magnetic field (AMF), the electrons are obliged to follow trajectories that are parallel to the field lines which are helical-shaped lines, the axis of which is parallel to the contact axis since $\vec{Ba}$ is combined with the azimuthal field produced by the current itself.

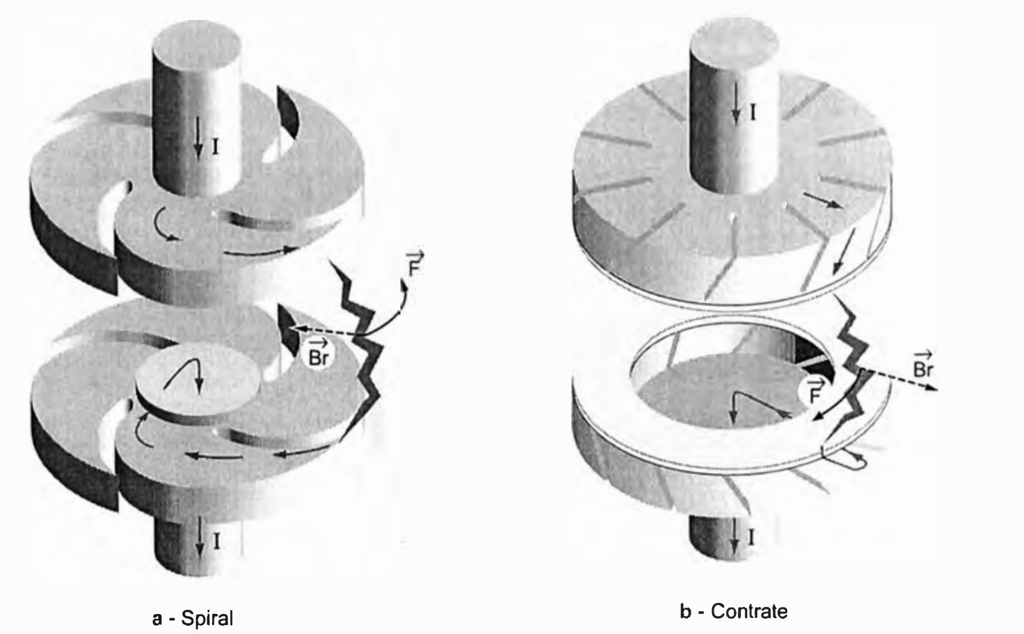


Fig. 10: contact structures used to create the RMF (spiral and "contrate").

The much heavier positive ions in the plasma are not controlled as efficiently by the field, but are retained by the electrostatic force developed by the negative space charge of the electrons trapped by the AMF: these electrostatic forces ensure that the plasma has a tendency to remain globally neutral. Consequently, electron confinement results in the confinement of all of the plasma in a column that corresponds to the field tube intercepted by the cathode: if this tube is parallel to the electrode axis, most of the plasma produced by the cathode arrives at the anode. The arc, in these conditions, conserves most of the diffuse mode characteristics although with a current density level that is considerably higher:

v the arc voltage remains moderate since the plasma conserves its neutrality up to near the anode (no ion "starvation" phenomenon);

v the tendency of the arc to concentrate on the anode side (the Hall effect) is interfered with by the AMF which forces electrons to maintain a trajectory that is essentially parallel to the axis;

v if the surface of electrodes, in particular of the anode, which is intersected by the arc column, is sufficient for the current, then the energy density and thus overheating remain limited. The vaporisation of contact material is sufficiently reduced so that the nature of the plasma is not modified by the ionisation of neutral particles.

Two main conditions need to be satisfied so that the arc remains in this diffuse column mode that is favourable to current interruption:

v Ba must be sufficiently high. The critical AMF needed to prevent the formation of an anode spot is given in the experimental formula:
$Ba_{crit} = 3.9\ (Ip - 10)$
(Ba in mT, with Ip peak current value in kA),

v the surface of the electrode must be sufficient for a given current value: the current density not to be exceeded is in the region of 17 A/mm^2 (RENTZ formula). In fact, this current density limit is only valid as a first approximation and the breaking capacity of interrupters with AMF does not change in direct proportion to the surface of the contacts. In fact, the initial constricted arc that was produced at contact separation and the time needed for it to occupy the entire available electrode surface must be taken into account: the breaking capacity, as a function of contact diameter, approximately follows a variation of $d^{1.4}$

The arc in an AMF interrupter is much less mobile than in a RMF interrupter. Even if the current density is sufficiently high to cause the fusion of anode material, projections remain limited. Contact erosion is therefore slighter than in a RMF, however the molton material remains in place and delays the cooling of the electrode surface. Due to this, even though in principle the use of the available contact surface appears more efficient in an AMF then in a RMF this is not always verified. In particular, for high currents and low voltages, in a RMF higher breaking capacities can be reached for a given surface, the price to pay however being significant erosion.

Diverse solutions can be used to obtain the AMF between contacts by using the current being interrupted:

v coils integrated behind the contacts (see **fig. 11**);

v a magnetic circuit that channels the azimuthal field created by the power leads and which straightens it into an AMF in the inter-contact zone;

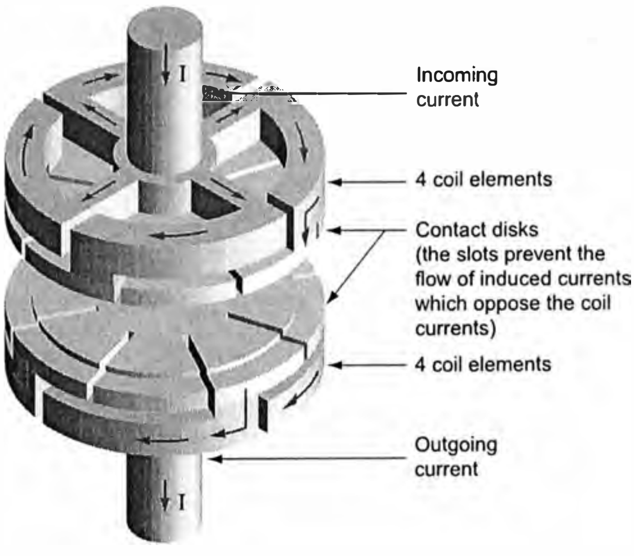


***Fig. 11:** example of axial magnetic field contacts .*

Fig. 12: axial magnetic field interrupter with external coil.

v an external coil that surrounds the inter contact zone (see **fig. 12**).

In general, the path imposed on the current, to create a sufficient AMF in the inter-contact gap, is longer than the one needed to create a local RMF. For a given volume, contact resistance is thus lower with the RMF technique, which is advantageous for circuit-breakers with high continuous current ratings.

However, the shapes needed for RMF contacts are more angular than those of AMF contacts and therefore less favourable on the dielectric level: the AMF is thus advantageous for high voltages.

The engineer thus chooses one of the two techniques in function of their respective advantages and depending on the foreseen application (see **fig. 13**).

Capacity:	**RMF technique**	**AMF technique**
High continuous current	+++	+
High voltage rating	+	+++
Electrical endurance	+	+++
Breaking capacity	++	++
legend: +++ = very good	++ = good	+ = average

Fig. 13: comparison table for the two breaking techniques

Choice of the architecture

c Vacuum interrupter components.
A vacuum interrupter is made up of few components (see **fig. 14**).

v Two electric contact assemblies of the butt type (since, under vacuum, sliding contacts would weld with each other); one is fixed, the other mobile. Each assembly includes a cylindrical electrode that conducts the current to the contact disks.

v A gas-tight enclosure including an insulator that ensures electric insulation between fixed and mobile contacts.

v A shield that protects the internal side of the insulator against condensation of metal vapour produced by the arc.

v A metal bellows which allows for the mobile contact to move while maintaining the enclosure tightness.

These are the basic components that are included in all interrupters. Moreover, in circuit-breaker interrupters, there are devices that generate magnetic fields (radial or axial) needed for breaking the power arc.
Variations are mainly possible at the shield level and on devices that produce magnetic fields.

c Shield configurations
The main choices at the shield level deal with:

v its fixing mode which determines its voltage: the voltage is fixed (is the same as that of the fixed electrode) if the shield is connected to this end of the interrupter, it is floating if the shield is fixed to an intermediary point on the insulator without an electric connection with one of the contacts.

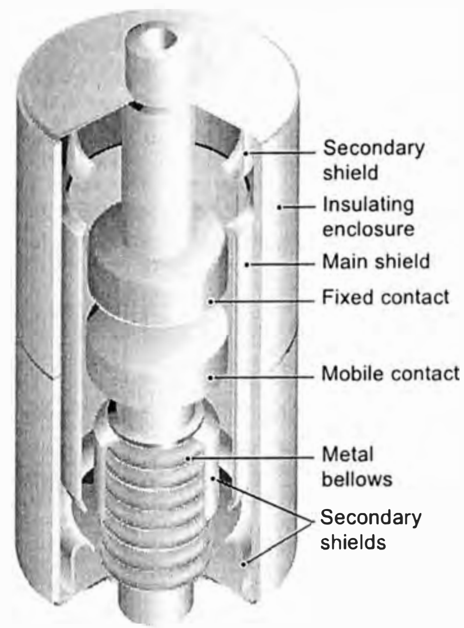


Fig. 14: vacuum interrupter components.

v its position which can be inside or outside the enclosure, in the latter case the shield is part of the enclosure and must be gas-tight.

By combining these different options, four configurations are possible, they are all used in function of desired characteristics.

As a general rule:

v a shield with fixed voltage is chosen when low cost is desired and a shield with floating voltage when high performance is sought.

v an external shield is chosen for compacity in diameter and an internal shield because it is simple to make.

c Devices that generate radial or axial magnetic fields
Devices that produce the RMF needed to rotate the arc must be positioned as close as possible to the arc: they are therefore built-into the same structure as the contacts inside the interrupter. The two most common geometries were described in the preceding chapter: "spiral" contacts and contacts of the “cup” or contrate” type. The choice of one solution over the other does not modify the general architecture of the interrupter.

However, there are two possible architectural choices for AMF interrupters.
In fact, the device that generates the AMF (most often elements of circular coils with an axis parallel to that of the interrupter) can be housed in the internal contact structure as with RMF interrupters, or outside of the interrupter. In the last case, there is a coil that surrounds the contact separation zone. The coil is in series with the fixed contact and the circuit current flows through it. **Figure 15** shows a realisation of this type of configuration: it can be noted that, to reduce the dissipated power in the device, the coil is made up of three parallel elements. One of the disadvantages of this architecture is the path length imposed on the current to create a sufficient AMF in a significant volume. This therefore leads to greater losses that however do not necessarily result in greater temperature rise, the coils in the air being more efficiently cooled (by convection) than those that are integrated into the contacts on the interrupter.

Moreover, the presence of a coil with the same voltage as the fixed contact, around the contacts, practically imposes the choice of a shield with a fixed voltage for this type of interrupter.

One might think that the presence of an external coil presents a disadvantage in regard to interrupter dimensions by increasing its external diameter. In fact, the possibility of using the entire contact surface that is subjected to the relatively uniform AMF created by the external coils (which is not the case for contacts that have integrated coils) compensates this disadvantage and dimensions are comparable. The main advantage of AMF architecture with an external

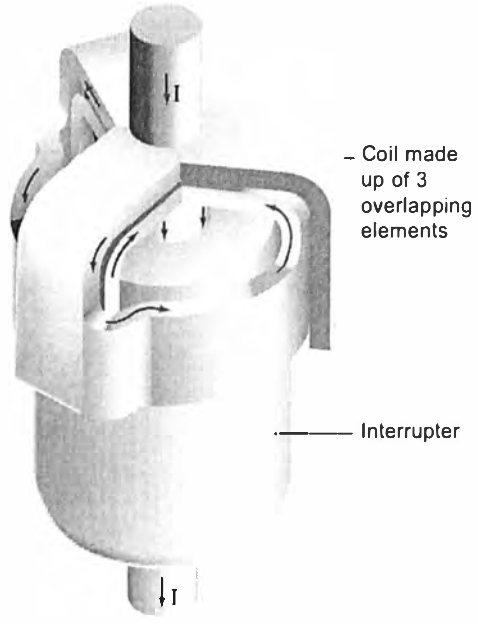


Fig. 15: example of a coil, surrounding the contact separation zone, made up of three parallel elements.

coil is the possibility of making a compact interrupter, simple thus economical. The disadvantages on the heat dissipation and dielectric levels (because of the fixed shield design) make the architectures with devices integrated into the contacts (AMF or RMF) more attractive for high voltage levels (u 24 kV) or for high current ratings (u 3150 A).

Choice of materials and manufacturing technologies

For vacuum interrupters, the choice of materials and manufacturing technologies are guided by the need to:

v guarantee the preservation of high-vacuum (< 10^{-3} mbar) needed to operate the interrupter for its life span (30 years),

v ensure the rated performances and in particular the breaking capacity.

c Choice relative to the requirements for vacuum quality
All vacuum chambers are subjected to deterioration of the vacuum level that is linked to degassing phenomena which appear when pressure reaches sufficiently low values. Degassing is first of all a surface phenomenon that corresponds to the detachment of gas molecules absorbed on the walls. This gas is rather easily and rapidly eliminated by relatively moderate heating (in the region of 200 °C) of the walls of the enclosure during pumping.

Then volume degassing, which corresponds to the diffusion, towards the surface of metal materials, of dissolved gases such as hydrogen, appears.
To prevent degassing, mainly coming from massive parts, from progressively degrading the vacuum level of the interrupter, it is important to:

v use materials with as low a gas content as possible (for example copper Cu-OFE oxygen free);

v proceed with high degassing of materials by conducting long-term pumping of the interrupter at a sufficiently high temperature (typically for some ten hours at a temperature in the region of 500 °C).

Gases bound to the metals (in the shape of chemical compounds) are not sensitive to degassing, however they can be freed under the arc effect. Therefore, the materials used for arc contacts must be elaborated in a vacuum environment so as to have the lowest possible gas content.

The enclosure of the interrupter must be perfectly tight, which implies the absence of leakages and permeation in service conditions. That is why enclosures are made of metal and ceramic materials: insulators made of alumina ceramic have replaced glass for they can tolerate much higher temperatures and thus allow for better degassing.

Bonding between the metal parts of the enclosure are welded or brazed. Ceramic and metal are also brazed, either using reactive brazing which enables a direct bond with the ceramic, or using traditional brazing by coating the ceramic with metal beforehand (Mo-Mn + Ni).

Final brazing operations are conducted in a furnace, under a vacuum to ensure the degassing of materials. More and more often, sealing of the interrupter is conducted during the brazing under vacuum process as well, which allows for the pumping operation to be eliminated.

Taking into account the tightness level needed to allow the mobile contact to move, the metal bellows is the only solution used. It is generally made of thin austenitic stainless steel (typically 0.1 to 0.2 mm). Its design and that of brazing joints with the rest of the enclosure must be carefully studied so as to ensure high mechanical endurance despite the unfavourable effect of thermal cycles imposed by brazing.

Lastly, materials that are used in small quantities, but which play an important role in obtaining and maintaining high-vacuum over time must be mentioned. Getters are based on very chemically active metals (barium, zirconium, titanium, etc.) with most of the gases that are likely to be found in vacuum enclosures. The getters are activated, under high-vacuum, through heating at a sufficient temperature to cause the diffusion of the passivated superficial layer into the bulk, and the regeneration of an active metal surface capable of absorbing the gas molecules that are in the interrupter. This activation operation is conducted during pumping or when the interrupter is sealed using brazing under vacuum: it is in particular due to getters materials that this last procedure, more industrial than pumping, while ensuring a satisfactory quality of vacuum, was able to be developed.

c Choice of contact material.
Good contact material for a vacuum interrupter must meet a certain number of requirements:

v be a good electrical conductor, so as to offer reduced contact resistance;

v present good mechanical resistance to repeated shock which the contacts undergo when closing;

v must not form solid welding upon on-load or short-circuit closings so that the opening mechanism can separate the contacts and so that the break of the welded zone does not create excessive damage to their surfaces;

v produce little metal vapour during the arc phase so as to enable rapid dielectric recovery of the inter-contact gap after breaking, which implies:
- low vapour pressure,
- reduced droplet production during the material fusion phase;

v present good dielectric characteristics during the TRV application phase, which implies:
- a sufficiently smooth surface, without any notable roughness (low β),
- no overheated points emitting by thermionic effect (case of refractory materials with reduced thermal conductibility),
- no likelihood of forming easily detachable particles;

v allow the existence of stable cathode spots up to low current values so as to minimise the chopped current and overvoltages associated with this phenomenon, which in particular implies a sufficiently high vapour pressure.

It turns out that these numerous required qualities are sometimes contradictory. It is thus necessary to find an acceptable compromise for the foreseen application in function of privileged properties which are:

v for circuit-breakers, dielectric recovery after the high current arc phase (good breaking capacity);

v for contactors, low erosion and minimum chopped current (electrical endurance and reduction of overvoltages);

v for switches, resistance to welding and dielectric withstand under high voltages (absence of restrikes).

Presently, the best compromises have been obtained with composite materials and the three material families that are the most often used are:

v CuCr for circuit-breaker applications;

v AgWC for contactor applications;

v WCu for switch applications and in particular those designed for the control of high voltage capacitors.

CuCr have been proven to be the best materials for circuit-breaker applications and do not appear to be able to be dethroned in the short-run, even if changes cannot be excluded.

Proportions used vary between 80 and 50 % for Cu, the remaining percentage for Cr.

A high proportion of Cu is favourable for the electric conductivity (low contact resistance) and thermal conductivity (good evacuation of arc energy).

A high proportion of Cr is favourable for withstanding welding and dielectric withstand under high voltage.

The gas content of material must be as low as possible since, when it is fused or vaporised, these gases are freed into the inter-contact gap and are harmful to breaking. The long-term effect on the vacuum level is less disturbing than could be imagined since Cr condensed on interrupter walls plays the role of getter and reabsorbs these gases.

Lastly it must be noted that the arc modifies the superficial layer of the material and improves its qualities by:

v eliminating included gases and surface oxides,

v obtaining very fine granulometry (precipitation of Cr melted in the copper matrix),

v homogenising material.

This effect is sometimes qualified as "current conditioning" (through analogy with voltage conditioning): in general the behaviour of contacts and the breaking performance improve after a few breakings.

3 Breaking in vacuum and overvoltages during switching of inductive circuits

Vacuum switching devices (contactors, circuit-breakers, switches) are likely to generate overvoltages when interrupting current in inductive circuits (no-load transformer, non-charged motor or motor in the start-up phase). Due to the special properties of vacuum, these overvoltages can be of a different nature than those generated in the same conditions by switchgear that uses another type of medium (air, SF6, oil, etc.).

In general these overvoltages do not pose a problem and do not need any special device. However in the case of sensitive loads (for example motors) it is recommended to install overvoltage limiting equipment.

3.1 Overvoltage generating phenomena

Overvoltage associated with an ideal breaking

Even in the theoretically perfect breaking case using an ideal circuit-breaker, a certain overvoltage level is inherent to the interruption of current in an inductive circuit. Indeed, voltage values at the terminals of different circuit elements must reach a new steady state that corresponds to the open state.

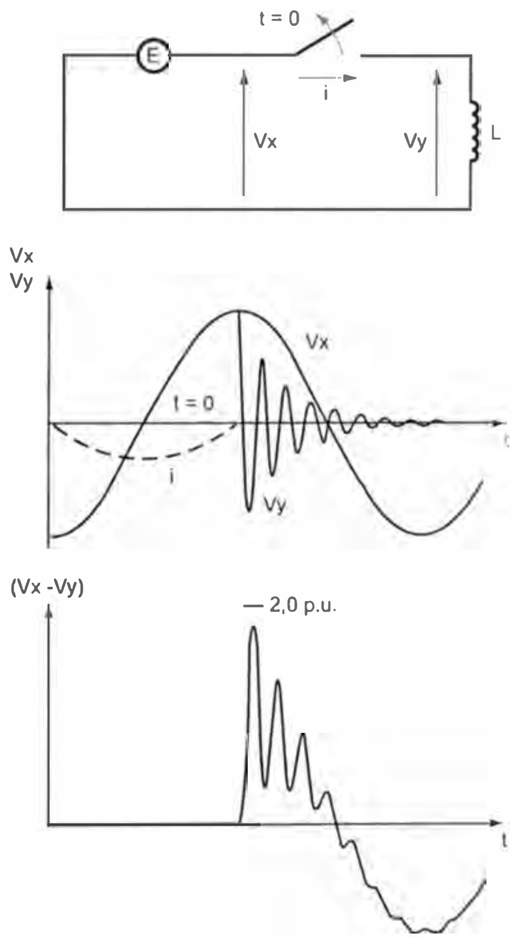
The transition in regards to the closed state preceding the breaking moment (current zero) leads to oscillations around the new steady state and produces overvoltages in comparison to normal maximum network voltage (see **fig. 16**).

In the case of a three-phase interruption, the fact that the interruption is not simultaneous on the three phases also introduces a transient state which generates overvoltages. As an example, in the case of the breaking of a short-circuit current in a system without a directly earthed neutral, the recovery voltage at the terminals of the first pole to clear reaches roughly 2.1 to 2.2 p.u. (IEC standardised TRV) and 2.5 p.u. for the breaking of a capacitor bank with isolated neutral.

Current chopping

The best known and most widespread phenomenon, for it deals with all breaking techniques, is current chopping: premature interruption of the alternating current before its natural passage through zero. This phenomenon above all concerns circuit-breakers, that are sized for breaking short-circuit currents, when they interrupt small currents.

If I_a is the chopped current value, current that flows in the load inductance L immediately before breaking, the electromagnetic energy that is stored in the load is transferred in the form of electrostatic energy in capacitance C located at the terminals of the load ($1/2\ L\ I_a^2 = 1/2\ C\ V^2$). A voltage increase on the load side appears which accentuates the gap in regard to the "open circuit" steady state and amplifies the



1 p.u. = maximum nominal phase to earth voltage

$$= \frac{Un\sqrt{2}}{\sqrt{3}}$$

Fig. 16: overvoltages in comparison to maximum normal network voltage during the breaking of an inductive circuit.

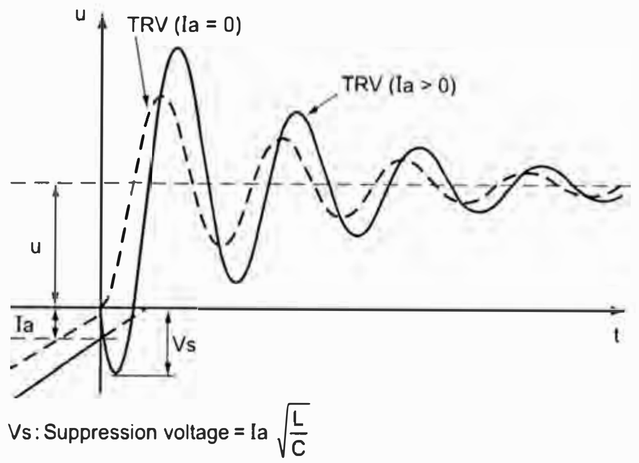


Fig. 17: overvoltages associated with the breaking of a circuit with current chopping.

overvoltages associated with the break (see fig. 17).

These overvoltages are therefore proportional to the chopped current and the characteristic impedance (surge impedance) $\sqrt{\frac{L}{C}}$ of the load.

In the case of vacuum switching, current chopping corresponds to the premature extinguishing of the last cathode spot due to its instability at low current values: this characteristic primarily depends on the nature of contact material. The average chopped current values for a few common materials are given in the following table (see fig. 18).

Material	$I_{chopped}$ ave.	$I_{chopped}$ max.
Cu	15	21
CuCr	4	8
AgWC	0.5	1.1

Fig. 18: average chopped current values for a few common materials (Cu, CuCr, AgWC).

In practise, chopped current values of a few amps, characteristic of the CuCr material, do not pose a problem. However values obtained using pure copper are excessive and explain, with other considerations, that this material cannot be used as such.

Multiple pre-strikings and re-ignitions

There is striking between the contacts when the applied voltage is higher than the dielectric withstand of the interval. This phenomenon is inevitable when this interval is very short (at the end of closing and at the beginning of opening).

Pre-striking upon closing thus systematically occurs when the operation is conducted under voltage: the time interval between the pre-striking and the moment when the contacts touch each other (pre-arcing time) depends on the closing speed and the voltage value applied at the moment when the contacts move closer to each other.

Re-ignition upon opening only occurs if the arcing time (time interval between contact separation and current break) is low: in this case the contact gap is not sufficient enough to tolerate the TRV and there is another dielectric breakdown.

During pre-striking or re-ignition, the oscillating discharge of local capacitances results in an HF current (some ten kHz) that flows between the contacts superimposed on the power frequency current that progressively establishes itself (as it is nil before ignition).

These inevitable phenomena concern all types of switchgear. The particularity of vacuum switchgear is their ability to interrupt HF current following striking whereas other breaking techniques are in general incapable of this due to high di/dt at the time this current passes through zero.

The breaking of HF current generates a new applied TRV between the contacts the gap of which has only slightly varied, for these phenomena occur on a small time scale in comparison to the contact movement time, which thus leads to new striking and repetition of the same phenomena (see fig. 19). There is a succession of multiple strikings associated with variable amplitude voltage waves depending on the change in the contact gap:

v upon closing the amplitude of the overvoltage train linearly decreases until the contacts touch each other,

v upon opening amplitudes increase until the gap between the contacts is finally sufficient enough to withstand the recovery voltage which, due to voltage escalation, is still higher than the voltage that corresponds to normal breaking.

Overvoltage trains with steep fronts, generated by these multiple striking phenomena, are

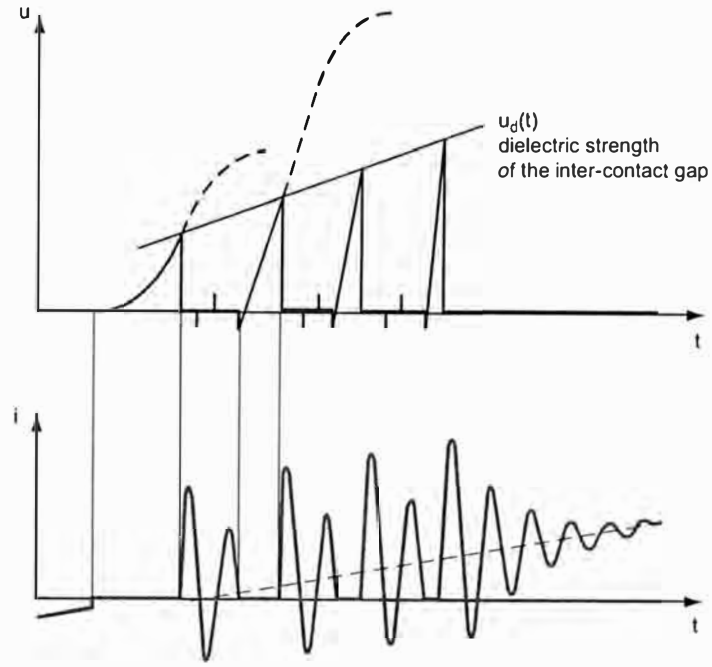


Fig. 19: succession of multiple strikings associated with voltage waves with varying amplitudes.

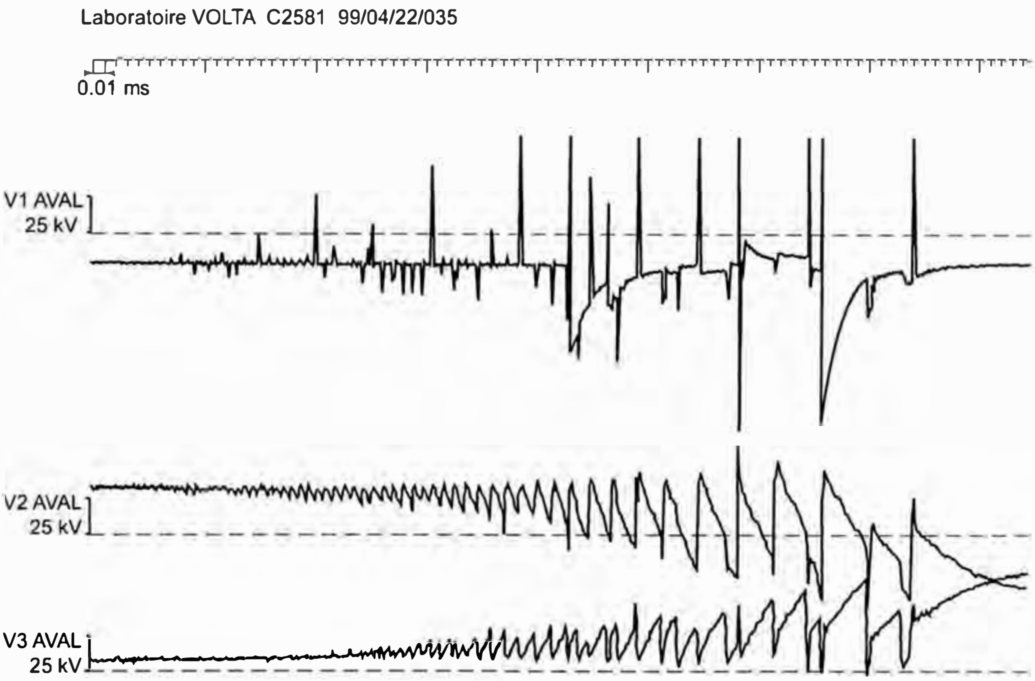


Fig. 20: multiple striking phenomena during contact separation and the breaking of small inductive current.

therefore still limited by the inter-contact gap that is maintained and which plays the role of spark-gap. However this limitation is only truly efficient upon closing; upon opening, the values reached can be high (see **fig. 20**).

The characteristics of these two types of similar phenomena are summarised in the table in **figure 21**.

Type of multiple striking	Occurrence	Amplitude of overvoltages
Pre-striking upon closing	Systematic	Low
Re-ignition upon opening	Occasional	High

Fig. 21: characteristics of overvoltages linked to multiple striking phenomena.

The disadvantage of these overvoltage trains are due more to their steep front than to their amplitude. In fact, these voltage waves with low rise times (in the region of 0.2 to 0.5 µs) are not distributed in a uniform manner in transformer and motor windings, rather they mainly stress the first turns (see fig. 22). They can therefore cause deterioration and accelerated ageing of the insulation between these turns.

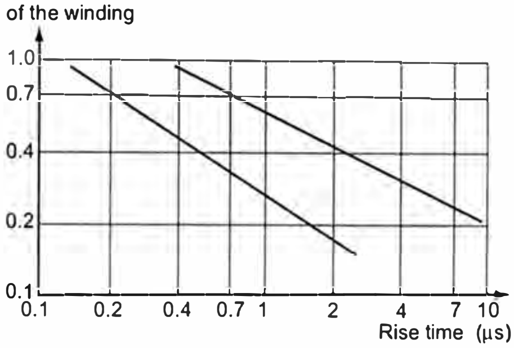


Fig. 22: percentage of the overvoltage applied to the first coil in the winding depending on the rise time.

Virtual current chopping

In special configurations (rarely encountered in practice) that are characterised by strong capacitive / inductive coupling between circuit phases, the multiple re-ignition phenomena on the first phase that attempts to break, lead not only to significant HF current oscillations in the phase dealt with, but also in the neighbouring phases in which a notable current still flows, for they are far from their natural zero.

If induced HF currents reach an amplitude exceeding that of the power frequency current, current zeros ("artificial" but nonetheless real, and not virtual) are produced. The device can take advantage of it to break the current well before its natural zero. In such cases the chopped currents can be tens, or even hundreds of amps and the associated overvoltages are very high.

A possible solution is to open one of the device poles in advance so that during the time interval when multiple re-ignitions are likely to occur, the two other phases remain closed and thus insensitive to induced disturbances. In practice, this solution has not been applied due to the problems that it poses (stress non-uniformly distributed between the poles during the breaking of a short-circuit current) and due to the exceptional character of the phenomenon.

3.2 Means of protection against overvoltages

"Soft" contact materials

Contact materials (ex: AgWC, CuBi) that have a very low chopped current value were developed for the contactor application. This performance was reached by combining low thermal conductivity with high vapour pressure so as to obtain stable cathode spots up to very small current values.

These characteristics go against the breaking capacity: that which is acceptable for a contactor application is not acceptable for a circuit-breaker application.

Furthermore, the use of these materials is only efficient in reducing overvoltages linked to chopped current, which does not pose a problem in practice if it does not exceed a few amps (case of CuCr).

"Soft" contact materials do not bring an improvement when compared with traditional "hard" materials (CuCr) on the multiple striking level. In fact these materials are also capable of breaking currents with high di/dt and are characterised by a slower dielectric recovery rate after contact separation (see fig. 23): consequently overvoltage trains with steep fronts are not eliminated but, on the contrary, have a tendency to remain longer than with better performing material for breaking.

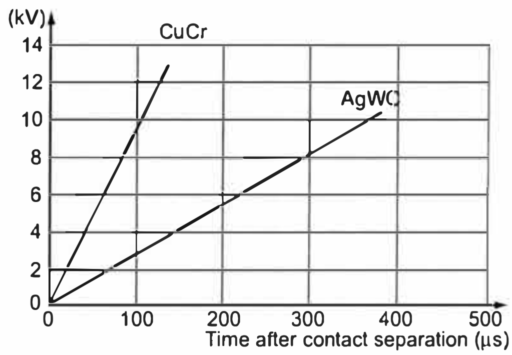


Fig. 23: change in the dielectric withstand between contacts from the moment of their separation depending on their materials.

Synchronised breaking

A theoretical solution to eliminate these multiple re-ignition phenomena would be to control the moment when contacts are opened in regard to the current wave so as to prevent short arc times. In practice, it poses complex reliability problems concerning the response time of the control mechanism; it is therefore only used in the High Voltage field where mastering switching overvoltages can justify the cost difference at the switchgear level. In the Medium Voltage field it is more economical to call upon overvoltage protection devices when a load is to be protected.

Protection devices providing overvoltage limitation

As mentioned above, the worst phenomenon is that of multiple strikings which calls primarily upon the first turns of transformer or motor windings. These two types of load must be taken into consideration separately.

Indeed, transformers are designed to tolerate dielectric stress generated by lightning impulses which are overvoltages with steep fronts, they thus have a good level of insulation of the first turns. Moreover the inductive currents to be switched are small (no-load transformer) and associated overvoltages remain limited.

As a general rule, it is not necessary to provide special protection for transformers that are operated by vacuum switchgear, except possibly for solid insulated transformers that are more sensitive than those insulated in oil.

Motors have a dielectric withstand lower than that of transformers, whereas the currents to be interrupted may be high (breaking in start-up phase or stalled rotor) and thus overvoltages are severe. As a general rule, it is recommended to place protective devices at terminals of a motor whatever its control device may be, contactor or circuit-breaker, and whatever the contact material used may be. These devices may be capacitors which reduce the rise time of overvoltages, or RC circuits (typically C in the region of 0.1 to 0.5 μF and R of 10 to 50 Ω) and/or ZnO surge arresters.

4 The main fields of application for vacuum switching

Vacuum properties as a breaking medium for electrical switchgear are summarized in the table in figure 24.

Field	Characteristics	Strong points	Weak points
Breaking capacity	Very rapid dielectric recovery	Breaking of fault currents with severe di/dt and TRV.	Breaking of HF currentsfollowing restrikes: overvoltages are generated, protection devices necessary in certain networks.
	Low arc voltage (energy).	High electrical endurance.	No current limiting effect in LV.
	Ability to break even without contact movement.	Current interruption in case of striking between open contacts (partly compensates for the lack of reliability of the dielectric withstand).	
Dielectric withstand	Influenced by the surface condition of electrodes and the presence of particles.		Intrinsic dielectric withstand limited in HV and may change over time.
	Influenced by the arc phase that immediately preceded.		Random post-break dielectric withstand: risk of re-striking after capacitive breaking if the interrupter is not adapted.
Current flow	Non-compensated contacts of the butt type.		High contact pressure needed to prevent "popping" by electromagnetic force.
	Contacts in vacuum.	Constant contact resistance (no oxidation and no deterioration upon breaking).	Tends to weld upon closing.
	Same contacts for continuous current flow and breaking.		High contact resistance: significant thermal dissipation for high ratings.
Breaking environment	Vacuum < 10^{-3} mbar.	No decomposition products and no effects on the environment.	Permanent monitoring of the vacuum level is impossible: periodic dielectric checks make shutdown necessary.

Fig. 24: vacuum properties as a breaking medium.

These strong and weak points of the vacuum switching technique have thus led to its use being favoured in certain fields of application for electrical switchgear. In the presentation that follows, the different fields of application are segmented in the following manner:

c by voltage level;

c then by function, or type of switchgear;

c lastly, depending on the type of load to be switched.

This chapter successively reviews the Medium Voltage (MV: 1< U < 52 kV), Low Voltage (LV: U < 1 kV) and High Voltage (HV: U u 52 kV) fields. The section that is the most developed is dedicated to MV which is the primary field of application for the vacuum switching technique. The LV and HV fields are only briefly described for the intrinsic limitations of vacuum switching only allow for this technique to occupy a marginal position: dominating techniques are breaking in air for LV and breaking in SF6 for HV.

.1 Vacuum switching applications in Medium Voltage

Medium Voltage is primarily used for electrical energy distribution, between the transmission over long distances that is carried out using High Voltage (HV) and use that is mainly carried out in Low Voltage (LV). The lower voltage levels of the MV field are also used to supply loads of unit power that is too high for LV.
In MV, the main types of switchgear that are used are switches, disconnectors, circuit-breakers and contactors (see **fig. 25**).

Switches are simple and relatively economical devices that are used in normal operation of electrical networks: they are operated upon an order coming from an operator and allow the current to be established or interrupted in a network element. They are capable of breaking the normal load current of the circuit in which they have been inserted, and to establish the fault current caused by a short-circuit located downstream from their position in regard to the supply of electrical energy.

General purpose switches that are designed for MV distribution networks, upon which the switching frequency is low, have, through their design, an electrical and mechanical endurance that is relatively limited, typically:

- some hundred breaks at In;
- some thousand mechanical operations.

For special applications, certain types of switches must be able to counter more severe stress, for example:

- switches for arc furnaces operate frequently with high currents;
- switches for back-to-back capacitor banks that operate rather frequently and must establish inrush currents (with high frequency and amplitude).

Disconnectors are not strictly speaking breaking devices for they operate without a load (they must however be able to interrupt the residual capacitive currents of open circuits). They are used to isolate a circuit from the rest of the network and allow for safe intervention on the circuit. To that effect, they must have a high dielectric withstand between contacts and must respect the construction measures that aim at preventing the crossing over of the isolating distance even in the case of overvoltage on the network. Despite these measures, the safety of persons intervening in the system is not fully guaranteed unless the network element that was isolated by a disconnector is earthed in an efficient manner as well. Disconnectors are often combined with switchgear that does not satisfy the disconnection function, in general circuit-breakers and contactors. Switches are, however, most of the time also able to fulfil the disconnection function: they are then referred to as switch-disconnectors.

Circuit-breakers are safety devices that protect the network by automatically separating the faulty sections of the network: they are able to interrupt maximum short-circuit current likely to occur at the place where they are installed.

Circuit-breakers can therefore be considered as high-performance switches that are capable of operating upon an order from an operator or

Type of switchgear	IEC definition	Applicable standard for MV
Switch	A switching device capable of making, carrying and breaking currents under normal circuit conditions which may include specified operating overload conditions and also carrying for a specified time currents under specified abnormal circuit conditions such as those of short circuit. (IEV 60050-441-14-10).	IEC 60265-1
Disconnector	A switching device which provides, in the open position, an isolating distance in accordance with specified requirements. (IEV 60050-441-14-05).	IEC 60129
Circuit-breaker	A switching device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time and breaking currents under specified abnormal circuit conditions such as those of short circuit. (IEV 60050-441-14-20).	IEC 60056
Contactor	A switching device having only one position of rest, operated otherwise than by hand, capable of making, carrying and breaking currents under normal circuit conditions including operating overload conditions. (IEV 60050-441-14-33).	IEC 60470

***Fig. 25:** standardised definitions of the main types of switchgear.*

from an automatic protection device that detects fault situations. These devices must be highly reliable since safety and network availability depend on their correct operation.

Circuit-breakers require higher electrical and mechanical endurance than switches, typically:

- from 10 to 100 short-circuit current breaks;
- from 2000 to 10000 mechanical switching operations and breaks at In.

Contactors are control devices for loads that function in an intermittent manner, notably electric motors. They are switches with high operating rates that must be able to break overload currents that are higher than nominal current (ex: starting motor or stalled rotor currents) but not short-circuit currents which are eliminated by a combined protection device (circuit-breaker or fuse). Their high mechanical and electrical endurance generally amounts to several hundred thousand operations.

The graph in **figure 26** enables the respective positions of the four types of switchgear described above to be visualised.

One of the strong points of the vacuum switching technique is its ability to obtain a high breaking capacity and electrical endurance: that is why this technique is primarily used for circuit-breakers and contactors.

Circuit-breaker application in MV

A high breaking capacity is required for a circuit-breaker application. Vacuum interrupters used for this application either call upon RMF technology, or on AMF technology. Both can reach the highest breaking capacities required in MV (up to 63 kA); they are thus used in function of their respective advantages (see fig. 13). As with SF6, vacuum offers for this application the advantages of an enclosed break with no external manifestations and a maintenance free design with high electrical endurance.

The very rapid dielectric recovery of the vacuum can be an advantage in comparison with SF6 in special applications for which the rate of rise of the TRV is faster than that required by the IEC 56 and ANSI C37-06 standards (ex: case of a circuit-breaker directly connected to the secondary of a high power transformer). In such cases, not very frequent for standardised TRVs cover the great majority of applications, vacuum circuit-breakers need less derating than SF6 circuit-breakers.

Since vacuum switching is conducted without an external energy supply, vacuum circuit-breakers require less operating energy than SF6 circuit-breakers of the puffer type. For that which deals with SF6 circuit-breakers with rotating arc or with self-expansion, the gap is less significant.

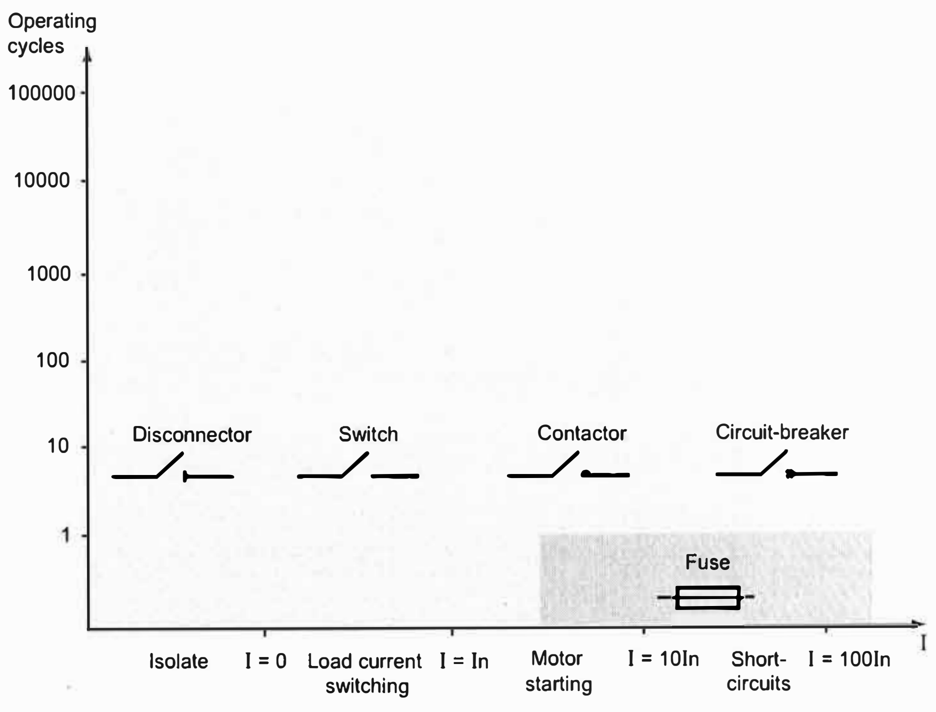


Fig. 26: respective positions of the four types of switchgear in terms of the current to be broken and of the number of operations to be conducted.

This advantage is however counterbalanced by the inherent disadvantages of the vacuum technique which can only use butt contacts. These contacts need high contact pressure to prevent repulsion and contact welding upon closing on fault: contact pressure needed per pole is in the region of 200 daN for a 25 kA circuit-breaker and of 600 daN for a 50 kA circuit-breaker. This requirement leads to a rise in the operating energy for closing and to reinforced pole structure that must tolerate these permanent stresses in the closed position.

Furthermore, despite high contact pressure, the use of butt contacts made of CuCr material does not allow for contact resistance as low as with silver-plated multiple contacts to be obtained: vacuum circuit-breakers thus have a handicap in comparison with SF6 circuit-breakers through higher thermal dissipation for high nominal currents (2500 A and above). Contacts in vacuum tubes, sheltered from oxidation, are not limited in overheating, unlike contacts of other circuit-breakers, but the interrupter's environment must evacuate the calories generated by it while respecting the admissible temperature limits on the connections and contacts; that is why vacuum circuit-breakers with high ratings are characterised by particularly large-sized connections and cooling fins.

Aside from their environment, vacuum interrupters are limited in overheating as well, not through the nature of the materials of which they are made or through their manufacturing process (high temperature brazing), but rather due to the properties of gas permeation through metal walls (in particular of the metal bellows) which become significant concerning atmospheric hydrogen as of 200-250 °C.

In conclusion, the vacuum switching technique is well adapted for general purpose circuit-breaker applications in MV and covers all of the normally required performances for voltage, nominal current and breaking capacity. For special applications such as the control of inductive or capacitive loads, special precautions must be taken, or other technologies may be better suited.

Contactor application in MV

This application is especially well adapted to the vacuum switching technique, which has acquired a dominating position in this segment. In fact, currents to be broken are located in the range of currents that are easily interrupted by diffuse vacuum arcing, with contacts that have simple shapes and low contact material wear, thence excellent electrical endurance. Contact pressure can be low, since nominal currents are modest and fault current is limited through the use of combined fuses, and even more so since the contact materials used have a very reduced tendency to welding and thus tolerate a certain degree of repulsion.

Supply voltages for MV motors located in the bottom of the MV range (in general i 7.2 kV) authorise a small contact gap (in the region of 4 mm) and the realisation of compact interrupters which have high mechanical endurance and are especially well adapted to electro-magnet operating mechanisms.

All these advantages explain the success of the vacuum switching technique for the MV contactor application. However, the risk of overvoltages during the switching of inductive circuits, which is specific to vacuum technique, must not be overlooked (motor in the start-up phase, no-load transformer) and the need for adapted protection devices (see chapter 3). This problem, which concerns all types of vacuum switchgear, must be especially taken into account in the case of motor switching, motors being loads that are sensitive to overvoltages.

Switch and disconnector applications in MV

The vacuum switching technique which allows for MV circuit-breakers and contactors to be made, can also, a fortiori, fulfil the more modest requirements of switches. It has however encountered limited success for this application. In fact, low performances can, in general, be obtained in a more economical manner by using breaking techniques in air or in SF6.

But above all, this function is often combined with the disconnector function, which is easily attainable using the air or SF6 technique, but not using vacuum. Combining a vacuum switch with a conventional disconnector makes this solution non-competitive.

The impossibility of ensuring disconnection with a vacuum interrupter is due to the voltage deconditioning phenomenon which is caused by the deterioration of the contact surface condition caused by mechanical and electrical switching operations. This deconditioning does not allow for the dielectric withstand that was obtained without any particular difficulty at the end of the voltage conditioning procedure on a new interrupter, to be guaranteed. Furthermore, it is impossible to continuously monitor the integrity of the dielectric medium in a vacuum interrupter which also limits its use as a disconnector.

With a switch, closing upon a short-circuit is particularly penalising for the dielectric withstand between contacts, for it is not followed by a fault current interruption that is capable of eroding the roughness caused by the break of the contact weld due to the pre-striking.

To prevent significant deterioration of their dielectric withstand, during consecutive closings upon short-circuit, switch contacts are made of materials that do not easily weld such as WCu, instead of CuCr which is used for circuit-breakers.

For special applications which require high electrical endurance (ex.: switches for arc furnaces), the vacuum switching technique is well suited and is widely used, even if overvoltage problems due to vacuum can, in certain cases, privilege the use of SF6 technology despite its lower endurance.

Another special application is that of the back-to back capacitor bank switch, which can be ensured by using a standard SF6 circuit-breaker, but which, using the vacuum technique, requires a special interrupter. In fact, the electrical charge of the capacitor induces a recovery voltage, applied to the terminals of the switching device, that is especially high. The post-break dielectric withstand of a vacuum interrupter is not its strong point due to the possibility of breakdown caused by the particles generated during the arcing period (see chapter 2).

In the case of capacitor banks in parallel that are separately closed, the risk of re-striking is accentuated by the effect of the high frequency inrush current due to the discharge of neighbouring capacitors in the one which is energised: this inrush current imposes the use of contact materials of the WCu type which do not easily weld and which is incompatible with the vacuum circuit-breaker application. Furthermore, to prevent attempts to interrupt HF inrush current during the pre-striking phase, which result in overvoltages that are harmful to capacitor banks, measures must be taken: the addition of surge inductances reduces the inrush current frequency, raising the closing speed reduces the pre-striking time.

In brief: the vacuum switching technique is not to be excluded for controlling capacitive loads, but other techniques, in particular the SF6 technique, are better suited.

.2 Vacuum switching applications in Low Voltage

The vacuum switching technique, widely used in MV for the circuit-breaker and contactor functions, can also fulfil the same functions in LV. It is however rarely used at this voltage level. In fact, on the one hand, it competes with the air breaking technique which is simpler, more economical and better adapted, and on the other hand, the disadvantages that have been noted in MV use are more disturbing in LV.

The main shortcoming of the vacuum switching technique in LV for the circuit-breaker function is due to the low arc voltage which cannot reach or exceed the network voltage like in an air circuit-breaker: it therefore cannot limit the fault current to a notably lower value than the prospective short-circuit current. This limiting effect is particularly useful for it avoids intense electrodynamic forces, that would be produced by prospective short-circuit currents that are often high in LV (up to 100 kA and above). This limiting effect also facilitates the natural selectivity between circuit-breakers for it is all the more accentuated, the smaller the circuit-breaker rating.

Furthermore, the disadvantages of vacuum interrupters, mentioned above for MV, that are linked to the use of butt contacts (high contact pressure and relatively high contact resistance), are more disturbing in LV power circuits which are characterized by high values of short-circuit currents (non-limited) and need higher continuous current ratings than in MV.

Lastly the high breaking capacity needed in LV imposes penalising dimensions for vacuum interrupters in comparison to air solutions for circuit-breakers with small current ratings.

For these different reasons, the use of vacuum interrupters in LV circuit-breakers is limited to a restrained section that corresponds to the following performances:

c breaking capacity i 75 kA,

c ratings between 800 and 2500 A.

In this context, even though vacuum switching is not cheaper than in air, it is worth considering for the following reasons:

c enclosed breaking with no external manifestations,

c use in polluted and explosive atmospheres,

c higher electrical endurance.

In LV contactor use, the disadvantages of vacuum interrupters, mentioned above for use in circuit-breakers are no longer to be taken into consideration. The main factors that slow down the development of this technique in this field are:

c first of all, the cost advantage in favour of classical air solutions;

c then, the specificities of vacuum concerning overvoltages generated during the interruption already explained in chapter 3.

In brief, in low voltage, the vacuum switching technique is not really able to compete with air breaking, except in special cases where enclosed breaking is significantly advantageous.

3 Vacuum switching applications in High Voltage

In the field of HV, the vacuum switching technique can be considered for use in the circuit-breaker function: diverse attempts have been made, without convincing success to date. In fact, it seems that the characteristics of vacuum switching do not allow it to truly rival the SF6 breaking technique in High Voltage.

One of the main difficulties to be overcome is the production of vacuum interrupters with a sufficiently high unit voltage rating. If vacuum interrupters capable of breaking under 36 kV are commonly made, already as of 52 kV it is often necessary to use two interrupters in series. Today, the highest voltage level at which a circuit-breaker equipped with a single interrupter per pole is available on the market is 72.5 kV.

Interrupters designed for use in applications at 123-145 kV are still, at present, in the prototype stage whereas SF6 breaking chambers up to a unit voltage rating of 420 kV are available. The solution which consists in placing a large number of interrupters in series to reach high voltages, above and beyond the technical problems that it poses (voltage distribution, reliability, etc.), can obviously not financially rival with the SF6 breaking technique. The main obstacle for obtaining a vacuum interrupter with a high unit voltage rating is the ceiling value of the dielectric performance for high voltages that is around 500 kV (see fig. 5), which corresponds to the lightning impulse voltage level to be reached for 123-145 kV devices. Presently, no technological solution is foreseeable.

Furthermore the use of vacuum at high unit voltage poses the problem of X rays that are likely to be emitted by interrupters subjected to supply voltages in the region of a hundred kV. Here we are dealing with voltage levels applied to MV interrupters to condition them: this operation is carried out in shielded enclosures so as to protect the operators against X-ray emission.

Using interrupters that have a dielectric design which is adapted to HV and already conditioned, the emitted radiation level (in the open position) should remain acceptable, but since interrupter operation can lead to partial deconditioning, this concern cannot be totally eliminated.

For physical limitation reasons, vacuum switching cannot therefore even come close to rivalling SF6 except for the lowest voltage levels in HV and only in unfavourable economic conditions. For very special applications, the combination of the two techniques, vacuum and SF6, can be foreseen, as was done for a 250 kV direct current circuit-breaker that uses a vacuum interrupter in series with an SF6 breaking chamber. This solution combines the qualities of vacuum, for breaking with high di/dt and initial TRV rate of rise, with those of SF6 which relays it to ensure withstand at the end of the TRV rise. For common HV circuit-breaker applications, it is not certain that hybrid solutions can rival on a financial level, with solutions that are 100 % SF6, even if on the technical level such solutions are attractive because they allow for the qualities of each breaking technique to be combined.

5 Conclusion

To conclude this overview, the vacuum switching technique appears, because of its good breaking capacity and electrical endurance performance, to be in general well adapted to circuit-breaker and contactor applications in medium voltage.

However the SF6 breaking technique is often better suited when privileged characteristics are dielectric withstand, low level of switching overvoltages or the ability to deal with high continuous currents.

Even though it has matured, the vacuum switching technique still presents notable potential for progress to be made concerning its performances, in particular using the relatively recent AMF technology. And so, the trend to reduction of the circuit-breaker interrupter size should be maintained. For this, progress is to be made in the optimisation of the use of contact surfaces and in the increase of permissible current densities. With these objectives, current research is primarily focused on:

c modelling of the arc and its interactions with the axial magnetic field;

c the mechanisms for diffusing and distributing the arc energy on the surface of contacts;

c improving contact material characteristics.

To widen the fields of application of the vacuum switching technique, and better use its qualities, switchgear manufacturers also foresee new solutions and notably its combination with other techniques, in particular with the SF6 technique, so as to combine their respective advantages. This approach is already used for certain medium voltage cubicles with gas insulation that unite the qualities of vacuum switching with those of insulation in SF6.

Another possibility, as of yet little explored, is the realisation of hybrid circuit-breakers that combine two breaking techniques, vacuum and SF6. A priori more expensive, it could however prove to be interesting in certain fields of application if it can efficiently conciliate the best of the two technologies.

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ANEXO G

PUBLICACIÓN TECNOLOGÍA 2006-2007 HITACHI

Healthcare Systems/
Biotechnology

HITACHI TECHNOLOGY 2006-2007

Industrial Systems

Industrial Systems
Steel and Chemical Plants
Environment
Public Facilities
Automotive Systems
Transportation
Building Systems
Semiconductor Manufacturing and Inspection Equipment

Power Systems

Information Systems

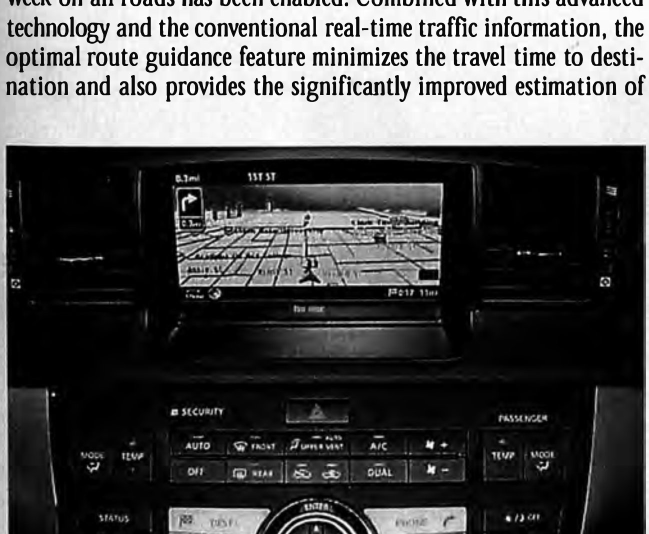
Car Navigation Evolving Toward a Safer, More Reliable, and More Comfortable Motorized Society

As the telecommunication network and transport infrastructure become increasingly developed, Hitachi Group decided to strengthen the business field of the CIS, and to accelerate the evolution of car navigation system and its role toward safer, more reliable and more comfortable motorized society.

Tomoaki Nakamura (left), Director CTO, HCX Corporation; Akio Sumizawa (middle), General Manager, Technical Development Center, Prior Development Headquarters, Xanavi Informatics Corporation; Hirohisa Miyazawa (right), Technical Development Center, Prior Development Headquarters, Xanavi Informatics Corporation

What is the Appeal of the Latest Car Navigation System Models?

Optimal route guidance feature won many users' reputation, provides significantly higher accuracy than the existing one, based on the Hitachi Group's unique traffic prediction technology. Since conventional practice uses the real-time traffic information sent from VICS (vehicle information and communication system) center and map information. It has a problem of road coverage. Fully used the extensive know-how of the Hitachi's research activities, Xanavi has developed an advanced technology that performs traffic jams estimations on all roads through the statistical processing of VICS information obtained over the past years. Thus the traffic jam estimation with higher accuracy for each hour and day of the week on all roads has been enabled. Combined with this advanced technology and the conventional real-time traffic information, the optimal route guidance feature minimizes the travel time to destination and also provides the significantly improved estimation of arrival time. The company will continue to commercialize new models of car navigation systems including this feature in Europe, the U.S.A., and Asia successively.



Latest models of car navigation systems

Xanavi mainly has provided OEM (original equipment manufacturer) products to the major car manufacturer in Japan, mounted in automobiles at their factory. Highly valued for its functionality and contribution, Xanavi received an innovation Award in 2005 recognized as one of the most valuable suppliers, from the major car manufacturer in Japan. Not only in Japan, also in Europe and the U.S.A., Xanavi has been accepted as a major supplier to manufacturers of onboard navigation system, and continuously expands its reputation towards a globally competitive company.

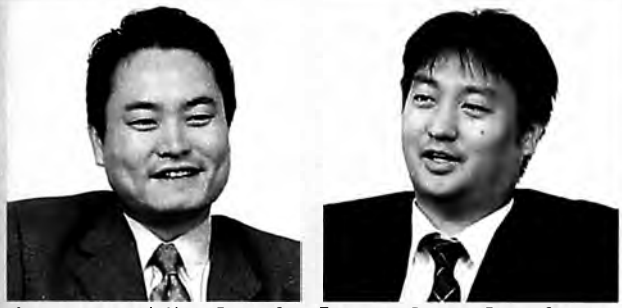
What is Happening to Car Navigation in the Near Future?

The progress of the information technology is making great strides in motorized society as well. With the introduction of the ITS car navigation, not only route guidance function, but also the advanced features equipped with telecommunication capabilities are emerging. Xanavi has joined the "Sky project" that involves field testing of the ITS to be conducted in Kanagawa Prefecture in 2006. In this project, car navigation will have the new feature to attempt to prevent traffic accidents and reduce traffic jams by using bi-directional communication between cars and traffic infrastructures. More specifically, several interesting experiments will be planned, such as on how to deviate traffic jams by warning drivers of incoming vehicles at an intersection, reminding drivers to observe speed limits in school zones and other areas of high pedestrian traffic, and "probing" location and vehicle information and send them to the traffic server. Even real-time micro weather forecast could be possible by monitoring the windshield wiper behavior of millions of cars.

Hitachi, Ltd. and Clarion Co., Ltd. established a comprehensive cooperation scheme in the CIS (car information systems) business in May 2005. It covers major supply chain activities such as R&D, procurement, production, sales, service and support. They also greatly increased the work force of HCX Corporation, a joint venture of the two companies, as a core development center for the 2008 and beyond model year products. By combining the IT (information technology) and automotive technology of the Hitachi Group with the car audio technology of Clarion, HCX will accelerate the development of car navigation products with high functionality, performance, and highly value-added features for the global market. To achieve the evolution of car navigation, highly reliable technologies related to both onboard equipment and server systems are required. Xanavi and Clarion will utilize the extensive expertise of the Hitachi Group and realize the safer and more comfortable motorized society.

Development of Japan's First Full Automatic Operation System for Subway and Series 3000 Train, Introduced in the Fukuoka City Transportation Bureau's Nanakuma Line Subway

The Fukuoka City Transportation Bureau's Nanakuma Line Subway that began service on February 3, 2005, is Japan's first subway line compatible with full automatic operation. Hitachi, Ltd. delivered a traffic control system and a train system to the project, helping to build a full automatic operation system for safe and efficient traffic. Hitachi also compiled the results of train developments, the first case of their kind, and took advantage of its long-cultivated experience and expertise to become a total integrator of railroad equipment. The company thus realized trains that combine the functional requirements for full automatic operation with excellent design performance and comfort.



Masahiro Fujiwara (left), the Rolling Stock Engineering Dept., the Rolling Stock Systems Div., Transportation Systems Div.; Naoji Ueki (right), the Rolling Stock Systems Design Dept., Kasado Works, the Industrial Systems

What are the Points of Full Automatic Operation in Subways?

Full automatic operation has already been introduced in new transport systems and similar facilities, but the Fukuoka City Transportation Bureau's Nanakuma Line Subway was the first to actually adopt such operation. Since subway trains run in enclosed tunnels, there had been concerns over the possible difficulty in taking refuge should a train be stopped between stations. For that reason, the present project for the full automatic operation system paid the greatest attention to three points: not allowing a train to stop between stations, not causing passengers needless worry, and ensuring stable travel. In so doing, Hitachi committed itself to building the system and equipment.

The greatest difference between the new system and conventional train control systems is that, in the event of an incident, the train reaches the next station, whenever possible, without stopping between stations. To that end, the units of train equipment related directly to travel consist of a dual system or a two-unit system, thus allowing one to run even if the other fails.

The traffic control system also employs a dual configuration for its main devices and constantly monitors the train status. Should a train fail, the on-board train operator enables cooperation with the personnel aboveground in order to take prompt action.

Full automatic operation is based on ATO (automatic train operation) and enables very precise operation control. Hitachi can safely say that a reliable, safe, and fully automatic operation system has been realized through a different way of thinking and a comprehensive review of conventional information transmission practices.

What are the Features of the Train?

The trains for the Nanakuma Line feature a new design based on the concept of friendliness to people and the environment. Compared to the commuter trains used for the old lines, this new train is three-fourths smaller in terms of length. However, the multiple configurations of train equipment described above require about double the amount of wiring. We brainstormed to find a way to manage the trains and eventually succeeded in combining a neat design with functionality by reducing the equipment size, considering an ingenious layout, and employing other features.

Conventionally most train equipment is developed by placing specific orders with respective manufacturers for a chassis, main circuit controls, motors, and air conditioners, and then having railroad operators organize their own projects. However, in the present project, we encountered the very first case where Hitachi, Ltd. received a collective set of orders and developed a completely new design. We were keenly aware that this new experience of developing the train in collaboration with members and non-members of the Hitachi Group would prove very valuable and beneficial.

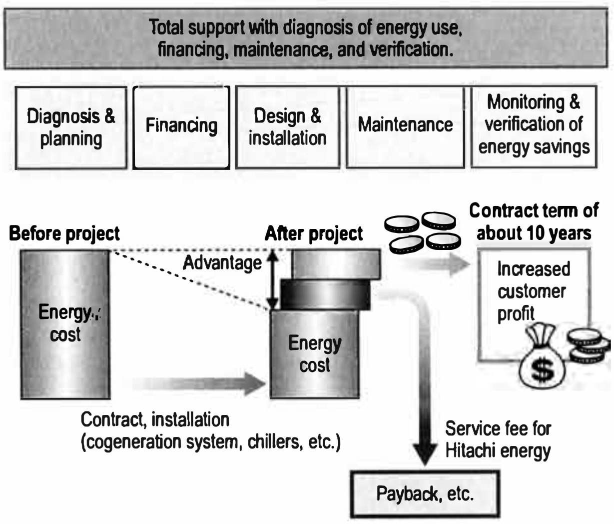
What are the Prospects?

For the Nanakuma Line, the traffic control system and train system—the very core of full automatic operation—were undertaken by Hitachi, Ltd. In addition, the company received a collective set of orders for all trains. We believe that all this happened because the client valued our capability resulting from long years of our comprehensive engagement in railroad projects. In the railroad field, the capability for providing such total solutions will be required more and more. We intend to continue enhancing our expertise in order to make our recent experience more useful in the future.

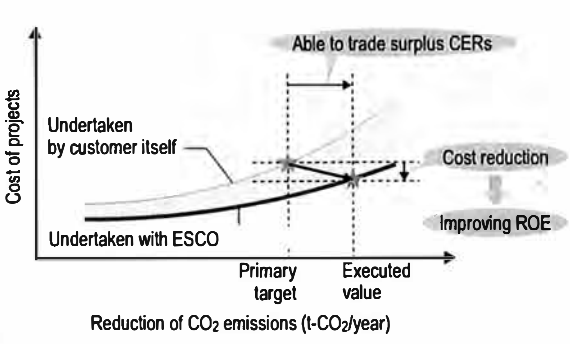
The series 3000 train delivered to the Fukuoka City Transportation Bureau's Nanakuma Line Subway

Hitachi Energy Solution Service in South East Asia

The Kyoto Protocol, COP3, determined at the third session of the Conference of the United Nations Framework Convention on Climate Change, has been in effect since February 2005. According to COP3, Japan has to reduce 6% of its emission of global warming gases between 2008 and 2012, compared to its levels in 1990. To meet this goal, the Japanese government has enacted several regulations for energy conservation, environmental taxes, emissions trading of carbon dioxide, and so on. This means that most companies and municipalities are required to severely reduce CO_2 emissions, energy costs, and capital assets.
Recently, the business of ESCOs (energy service companies) has been growing, and they have been providing customers with comprehensive services for energy savings. Hitachi started an ESCO business in April 1999, and it currently is involved in about 100 projects.
The ESCO has a new business scheme that offers comprehensive services for energy savings to customers and covers the cost required to repair energy-saving equipment with the money saved by the energy saving. The service includes an energy saving diagnosis, energy saving proposal, equipment installation, finance, and maintenance.
Reducing carbon dioxide emissions is very important; however, customers request not only reduced carbon dioxide emission, but also reduced energy costs and reduced costs of products for improving ROE (return on equity).
The Hitachi's ESCO manages to comprehensively reduce carbon dioxide emissions and to save more energy and product costs compared with projects promoted by customers themselves. Therefore, it can effectively trade surplus CERs (certified emissions reductions) and improve ROE.
The following are advantages of working with the Hitachi's ESCO to save energy costs: (1) total execution of energy-saving modifications, (2) reliable advantage with only a flat service fee, (3) effective investment for core business to improve ROE, through capital asset reduction.
Additional characteristics of Hitachi are as follows:
(1) Hitachi already produces various products for energy saving and has experience in various fields all over the world.
(2) A monitoring system has been established for cogeneration and other energy saving systems in Japan and has been expanded to South East Asia.
(3) Hitachi has profound knowledge of its products and knows when maintenance should be done.
Hitachi has started an ESCO with Hitachi Asia Ltd. in South East Asia. Its first project is the Energy Saving Service of Hitachi Global Storage Technologies Philippines Corp. as shown in the figures below.
In this project, Hitachi installed a waste heat recovery system in an ordinary diesel engine generator so that the waste heat of the engine jacket water and exhaust gas are converted into cooling chilled water by efficient hot water and steam absorption chillers. The energy saving value is about one thousand kiloliters per year in crude oil.



Concept of ESCO business



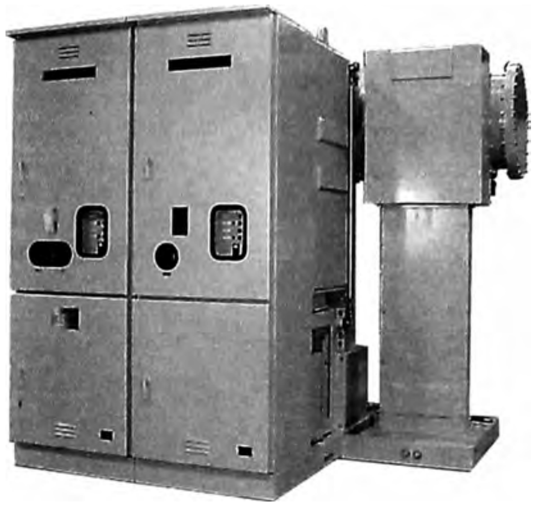
Goal of ESCO business

Exhaust heat steam boiler

Steam absorption chiller

Environmentally Friendly Gas Insulated Switchgear

The International Conference on Global Warming in December 1997 called for the reduction of SF_6—the common gas used in GIS (gas-insulated switchgear)—because it is a greenhouse gas, and this Kyoto Protocol became a legally binding treaty on February 16, 2005. Committed to provide an environmentally friendly GIS, Hitachi was first to develop and deploy dry-air-insulated switchgear based on a VCB (vacuum circuit breaker) and dry-air insulation technology, and this new system was put into service in June 2005. Building on this success, we are now moving toward completion of an environmentally friendly substation that uses a silicon oil transformer.



Environmentally friendly GIS (72-kV rated voltage, 800-A rated current, and 25-kA/2-s rated short-time withstand current)

Hitachi Industrial PC

HF-W6500 model 20

Hitachi has now released HF-W6500 model 20, a PC designed for industrial and manufacturing uses. The PC has high reliability and can be used in communications and semiconductor fab line systems where processing performance, reliability, and maintainability are critically important.

[Main features]

(1) Designed for high reliability, the PC can run 24 hours, 365 days a year for ten years.

(2) Long-term availability of the same computer model guaranteed for at least three years after the model first goes on sale

(3) High-performance, low power consumption Intel Pentium* M 745 (1.8 GHz) is adopted.

(4) ECC (error check and correction) memory is used for high reliability.

(5) Fault monitoring and analysis services are available.

(6) Hardware RAID (redundant array of independent disks) is available.

(7) Fully compliant with RoHS (restriction of hazardous substance) directives

(8) Compliant with UL, CSA, CE, FCC, and CCC international standards

* See "Trademarks" on page 94.

High-speed PXR Series Inkjet Printers for Manufacturing Lines

High-speed inkjet printer PXR-H450W for manufacturing lines

Hitachi has now launched the industrial inkjet printer PXR series to meet the demanding requirements of customers in the beverage, food, cable, and steel industries for high-speed printers on fast-moving manufacturing lines.

[Main features]

(1) The PXR series features a newly designed nozzle and enhanced electronic control over ink droplets deposition. The number of ink droplets used in printing has been substantially increased to 95,200 per second, approximately 1.4 times more than on the previous model. Two-line printing performance is more than adequate to keep up with the fastest manufacturing lines in the world moving at 150 m/min.

(2) Hitachi also developed new specifications for the print-head and ink droplet control scheme specifically for this line. The printer produces exceptional print quality even on the fastest moving manufacturing lines.

(Hitachi Industrial Equipment Systems Co., Ltd.)

Large Air-cooled Two-stage Oil-free Screw Air Compressor

Oil-free screw air compressors are used in many industries that have environment-related needs, such as food and chemical factories which require oil free air. Large air-cooled models, 132–240 kW, have been newly developed.

[Main features]

(1) Newly developed air end enables the highest performance in this air-cooled model.

(2) Low noise design is achieved by improved vibration proof structure for the drive train components. In addition, the noise of the intake and exhaust air for the cooling air is also reduced. Even if it is compared with the water-cooled model, the noise level is still competitive.

(3) Coolers are installed in parallel and on the angle like V-shaped. Space saving design is achieved by this unique cooler layout and downsized gear case.

(4) The new air ends and Hi-precooler system enable the discharge pressure to be up to 1.0 MPa.

(5) No water quality management is required, and the structure enables easy cleaning of coolers.

(Hitachi Industrial Equipment Systems Co., Ltd.)

(Sales started: December 2005 for export)

Large air-cooled two-stage oil-free screw air compressor

High Energy-saving Super Amorphous Transformers

Compact super amorphous transforrner

In an effort to reduce energy losses and greenhouse gas emissions, the Japanese government enacted the Energy Saving Law, designated amorphous metal transformers for their high energy saving potential, and declared 2006 the target year to achieve the top runner standard of 30% loss reduction over conventional oil-immersed transformers.
Hitachi's compact and lightweight super amorphous transformer was the breakthrough needed to finally achieve the top runner standard, and this series of transformers is now available on the market. By substituting amorphous alloy for the core material, we have now exceeded the top runner standard by more than 30%, and have developed a whole line-up of super amorphous transformer products to help conserve energy and reduce greenhouse gas emissions.
(Hitachi Industrial Equipment Systems Co., Ltd.)

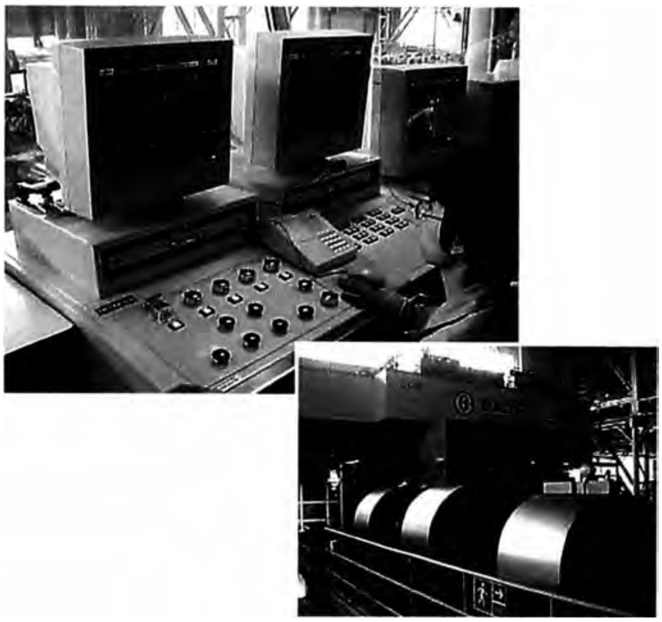
Electrical Equipment for Advanced Continuous Pickling Cold Rolling Delivered to BNA in China

Electrical equipment for advanced continuous pickling cold rolling delivered to Baosteel-NSC/Arcelor Automotive Steel Sheets Company (BNA) in Shanghai, China, is now in commercial operation and running smoothly.
BNA is a joint venture among Baosteel, Nippon Steel, and Arcelor, and this cold rolling equipment is the first installed at the company. The new equipment will be used to produce a full range of steel sheets from 0.35-mm thin sheets to medium-thickness high grade steel sheets for car bodies. The combination of high-response multi-functional 10-MVA high-voltage IGBT (insulated gate bipolar transistor) drive equipment with a strip-thickness control system based on optimum control theory, enables the company to produce high-precision and uniform-quality steel sheets over their entire length. Strip shape quality and operation stability have also been markedly improved through the introduction of a new strip shape control technology. A key advantage of this new shape control scheme is that it supports precise control all the way to the edges of strips and well beyond the range of the previous system, so now precision shape quality is extended over the entire width of steel sheets.
(Start of commercial operation: March 2005)

Central operation room (above) and high-voltage IGBT drive equipment (below)

Double Cold Reduction Mill for Baoshan Iron & Steel Company, China

A DCR (double cold reduction) mill was delivered to Baoshan Iron & Steel Company (Baosteel) in China and has been up and running smoothly since February 2005.
China's first DCR/temper 2-stand tandem mill for the production of DR (double reduction) tinplate, the equipment is a 6-high UC (universal crown) mill that can readily change work-roll diameter, supports both dry and wet production modes, and features the latest electronic control technology that is capable of producing very thin sheets to a gauge of only 0.1 mm. The sheet gauge precision across the entire coil including head and tail ends is significantly improved by introducing a high-performance multi-functional IGBT (insulated gate bipolar transistor) drive unit and high-precision gauge control technology for application to ultra-thin rolling. By adopting a new shape control technology that optimally controls the work-roll and intermediate-roll bender, shape control has been markedly enhanced while maintaining excellent operation stability.



One-person operation in the main control room (above), the mill equipment and cold-rolled coils (below)

Six Hitachi-supplied Processing Lines Commence Operation in Overseas Markets

Fiscal 2005 saw a succession of six Hitachi-supplied steel mill lines commence operation in overseas markets: a continuous annealing line and No. 1 continuous galvanizing line for Shanghai-based Baosteel-NSC/Arcelor Automotive Steel Sheets Company (BNA), the No. 2 continuous annealing line and No. 5 continuous galvanizing line for Pohang Iron & Steel Company (POSCO) in Korea, and a continuous galvanizing line and continuous coating line for Hyundai Hysco also in Korea.
All this investment reflects a growing demand for cold-rolled steel sheets as building material and to manufacture cars. To ensure high quality, precision tension control was implemented based on Hitachi's responsive multi-functional IGBT (insulated gate bipolar transistor) drive equipment. The effectiveness of Hitachi's SPM (skin pass mill) shape control deployed at BNA's continuous annealing line is also clearly apparent, for the continued praise this and the other companies receive for the steel sheets supplied to the auto makers who have a very exacting standard of quality.

Operation control room (left) and delivery equipment (right)

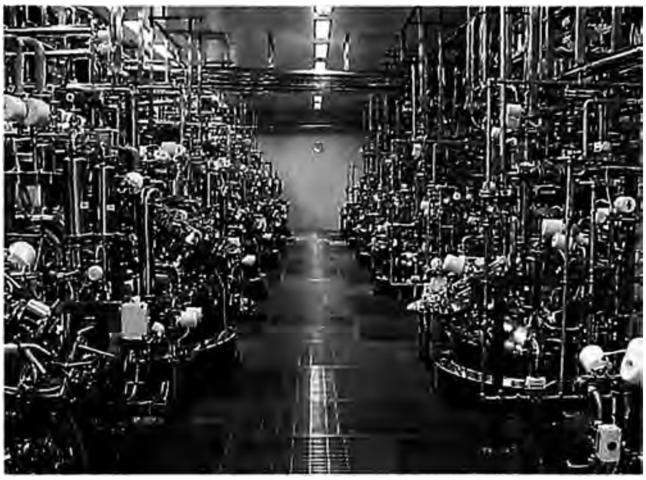
World's Largest Class Mammalian Cell Culture Plant Supplied to Chugai Pharmaceutical Co., Ltd.

Antibody therapeutics based on genetic information and sophisticated protein processing technology has been developed extensively because of its high efficacy and low side-effect potential. To produce high molecular-weight antibody therapeutics in intact condition, reliable and highly productive mammalian cell cultures are indispensable.

Hitachi supplied a first-phase antibody production plant in Utsunomiya, Japan in September 2002 for Chugai Pharmaceutical Co., Ltd., which was the largest Japanese mammalian cell culture plant. The world's largest class scale antibody therapeutics manufacturing plant was supplied as the second-phase plant in May 2005.

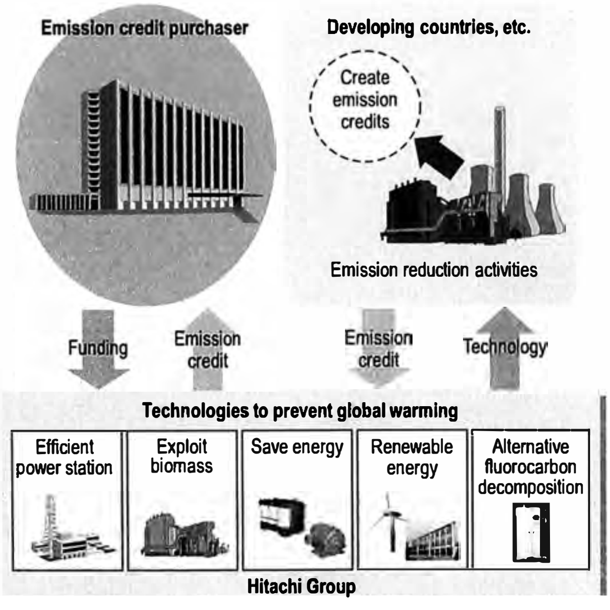
This second-phase plant was engineered using Chugai's improved manufacturing process and Hitachi's proven fermentation technology with computational fluid dynamics. The manufacturing process includes six 10-kL cell culture reactors, cell separation, column chromatography, tangential flow filtering, and bulk filling. Hitachi provided engineering, procurement, construction, and validation services complying with current good manufacturing practices for the entire plant.

Significant productivity enhancement is expected using the improved process and optimized equipment through full-load operation.



World's largest class mammalian cell culture plant: six 10,000-L scale mammalian cell culture reactors

CDM/JI: Emission Reduction Projects with International Partners



Overview of international projects (CDM/JI) to roll back global warming

The Kyoto Protocol committing the advanced industrialized nations to curtail and roll back greenhouse gas emaciations went into effect in February 2005. Japan would find it extremely difficult to meet its emission reduction target of −6% based upon domestic projects alone, and is thus seeking to obtain emission credits through public and private emission reduction projects with international partners through the CDM/JI (Clean Development Mechanism and Joint Implementation) arrangements provided for in the Kyoto Protocol.

The Hitachi Group is recognized for its many energy-saving products and systems designed to reduce or decompose greenhouse gases, and now Hitachi is moving aggressively through the CDM/JI to transfer these products and systems to other countries. Specifically, Hitachi is formulating CDM design documents for submission and approval by the United Nations to conduct emission reduction projects in collaboration with international partners. We are pursuing this approach not only to help Japan meet its emission target in a cost effective way, but also to help roll back global warming by transferring our technological knowhow overseas and to assist developing countries achieve sustainable development.

Central Monitoring and Control System Deployed at Niwakubo Water Purification Plant in Osaka Department of Waterworks

Department of Waterworks Osaka Prefectural Government Mishima and Expo Park water purification plants (with a combined processing capacity of 330,000 m^3/d) have been converted to unmanned facilities thanks to the deployment of a remote monitoring and control system. The satellite plants are now controlled through a central monitoring and control system installed at the Niwakubo Water Purification Plant.

|Main features|

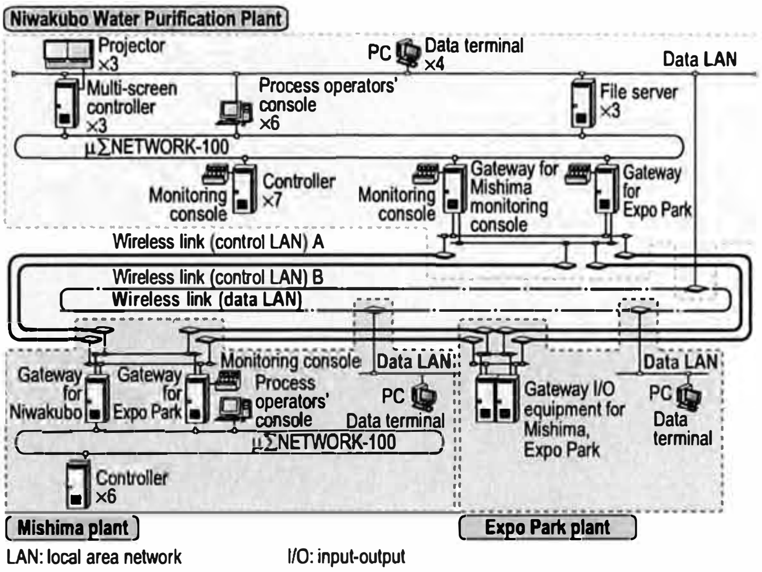
(1) Remote monitoring and control using a LAN for communication among the various plants over independent wireless links.

(2) Reliability is assured with redundant implementation of wireless links and monitoring equipment.

(3) In the addition to the control LAN, another wireless LAN is deployed for exchanging information and accessing the plants.

(4) The system includes fault monitoring to pinpoint network failures.

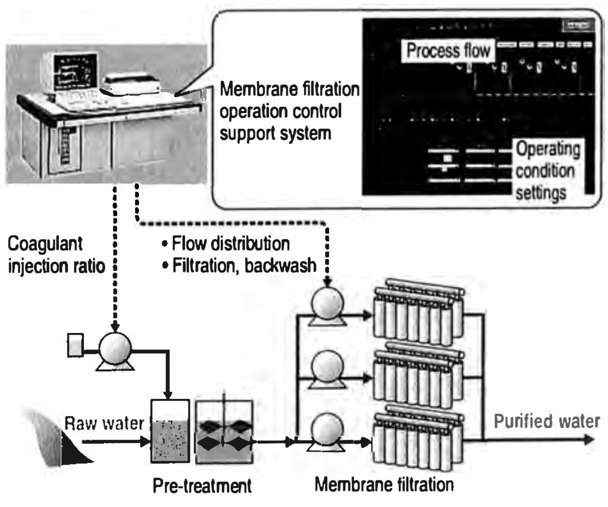
(System began operating: January 2006)



Configuration of the new monitoring and control system

Membrane Filtration Operation Control System for Water Treatment

A growing number of medium- to larger-scale water purification plants are planning to introduce membrane filtration processes not only to enhance the efficiency of their plant operations management but also to better filter out protozoan pathogens. In membrane filtration processing, the distribution of water flow through numerous membrane filtration units, the amount of pre-treatment, and the operation of the membrane filtration equipment are all closely interrelated in a complex way, so it's essential that the various operating conditions are properly set considering the operation of the plant as a whole. To assist in this difficult balancing act, we developed a membrane filtration operation control support system that effectively couples a membrane fouling model, a pre-treatment model, and a flow distribution model. This support system permits various control conditions to be evaluated in terms of their impact on the total operation of the plant, and thus helps reduce plant operating costs.



Overview of the membrane filtration operation control support system

Assessing Total Environmental Load Discharge from Sewage Treatment Plants

Fundamentally important issues in sewage treatment are the reduction of greenhouse gas emissions in line with the Kyoto Protocol and the reduction of pollutant discharge into the water in accordance with regulations on water quality and total allowable volume of pollutants, and ways to improve the operation of existing plant facilities and ways to upgrade equipment and systems are being investigated.

With the goal of quantitatively assessing the effects of efforts to reduce the environmental load of sewage treatment plants, we developed a new method for evaluating various environmental load factors—treated water quality, quantities of power, chemical agents, sludge, and greenhouse gas emissions—based on water treatment and sludge treatment process models by inputting the amount of sewage influent, plant equipment conditions, and operating conditions.

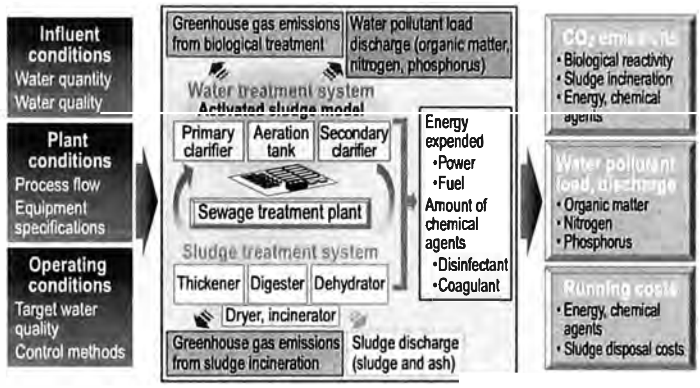
[Main features]

(1) The method factors in the sludge cycle between water treatment and sludge treatment systems, hence assesses the total environmental load of discharge from the sewage treatment plant.

(2) An activated sludge model is applied to the water treatment system that enables the amount of sludge discharge to be calculated for the any influent condition of the treatment plant.

(3) The method is especially useful for evaluating environmental load and cost-effectiveness in modifying the operation of existing facilities, and revamping or upgrading plant equipment.

(Announced: October 2005)



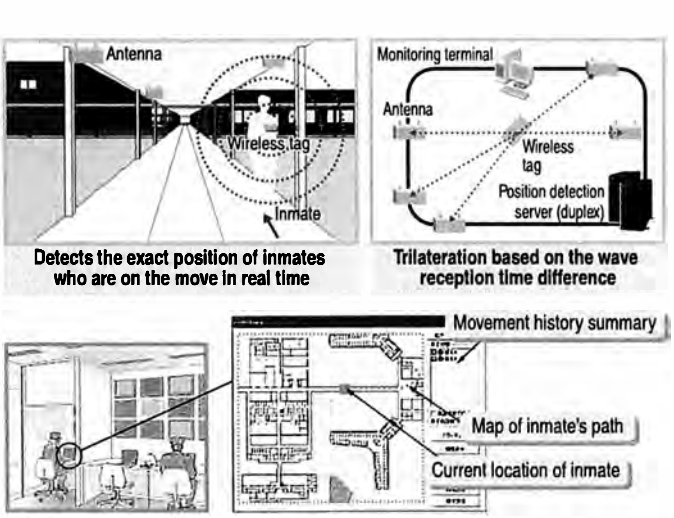
Overview of environmental load assessment at sewage treatment plants

Ministry of Justice Correction Bureau's Mine Rehabilitation Program Center Establishment and Operation Project: Tracking Solution for Inmates

To alleviate overcrowding in Japan's prisons due to worsening crime rates, Japan is in the process of setting up a program called through PFI (private finance initiative) in which inmates are confined to designated security zones. Participating in a consortium led by SECOM Co., Ltd., Hitachi proposed an inmate tracking system that satisfies the stringent requirements of the program, and in April 2005 the Ministry of Justice Correction Bureau approved and ordered the system.

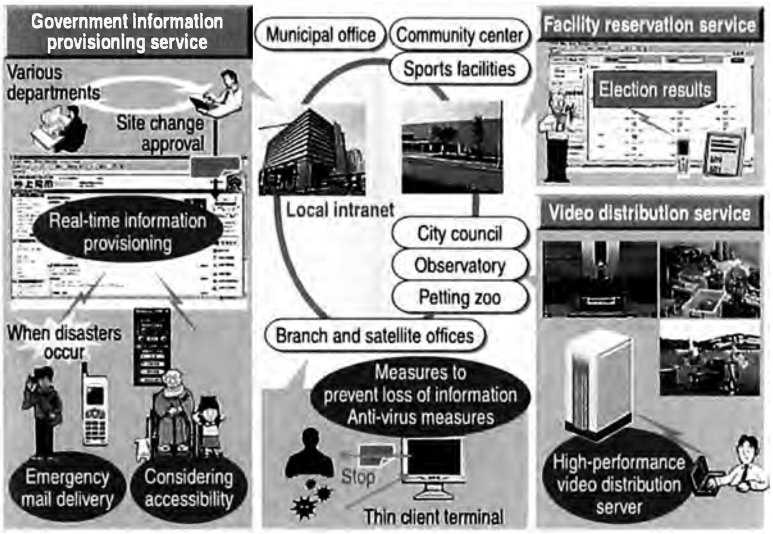
Essentially the system consists of a wireless LAN position information system that tracks and detects the exact position of people with pin-point accuracy called AirLocation and wireless tags that inmates cannot remove. This ensures that inmates can be located within the designated security zone at all times. Position information can be obtained in real time anytime on a monitoring terminal, a solution that not only alleviates the burden of guarding the inmates but also should make the entire operation much more effective and efficient.

(System scheduled for deployment at the Center: April 2007)



Tracking solution for inmates

Government Information Provisioning System for the City of Ageo, Japan



Overview of government information provisioning system for the city of Ageo

A new government Information Provisioning System has been set up in the city of Ageo in Saitama Prefecture that gives the local people access to a wide range of advanced public services in real time.

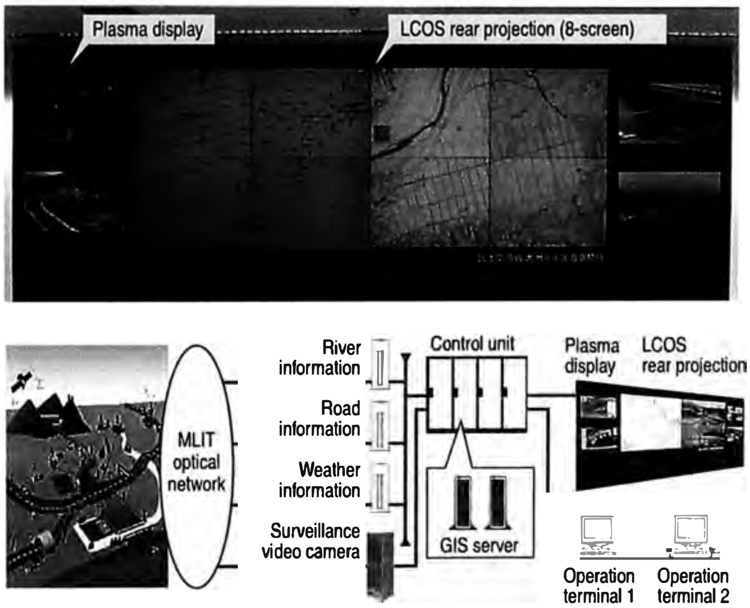
In this system, site pages can be edited and approved very easily, and the system offers live information with improved visual accessibility. Citizens of Ageo have already expressed strong approval for the system. They find it very useful for reserving public equipment and facilities over their cell phones and for checking on election results. The system also features a high-performance video distribution server that enables the local people to watch meetings and conference proceedings of municipal assembly on their own home PCs or to enjoy live feeds of stargazing through the local observatory telescope or from the local petting zoo.

(Delivered:February 2005)

River and Road Disaster Information System for the Oozu River & Road Office, the Ministry of Land, Infrastructure and Transport

Hitachi was commissioned to supply a state-of-the-art information support system to the Oozu River & Road Office—a district that is frequently hard hit by typhoons and torrential rainfall—to help alleviate disasters affecting local roads and diverted rivers.

The system is now installed in the disaster prevention office of a new building recently constructed as a disaster preparedness center for local rivers, roads, and communities. The system features a total of 12 displays that provide a comprehensive overview of weather information (rain volume), river information (sluiceways, dammed basin reservoirs), and road information (road surface conditions, road blockages, and other restrictions) for the entire district superimposed on detailed GIS (geographic information system) maps. The ability to show displays and manipulate strategically placed video surveillance cameras also aids in quick decision-making and developing appropriate disaster countermeasures.



LCOS: liquid crystal on silicon MLIT: the Ministry of Land, Infrastructure and Transport

Images superimposed on GIS maps and system configuration

Hazardous Substance Detector Using Mass Spectrometry

ased on a novel counterflow atmospheric-pressure chemical ionization technique, Hitachi has developed a new type of detector that is capable of identifying a wide range of hazardous materials including explosives, illegal narcotics, and dangerous chemical agents. A prototype explosives trace detection system was unveiled in March 2000, and the same basic approach was subsequently used to develop narcotics and chemical agent detection systems.

After the string of coordinated terrorist attacks in 2001, the US Transportation Security Administration (TSA)—an agency well known for its expertise in security matters—procured several thousand of ETD (explosives trace detection) system for deployment in US airports. In 2003, Hitachi's ETD system DS-110E-W was developed and certified by the TSA in May 2005, the first time that a non-American manufacturer of this kind of system has received TSA certification.

We are now stepping up efforts to sell these systems to airports and other critical infrastructure facilities in Japan and elsewhere, while at the same time continuing to refine and improve the performance of the detection systems. Hitachi has applied tandem mass spectrometry technology for the detection of illegal narcotics and chemical agents, a major improvement that will markedly speed up the hazardous material identification process. This will give law enforcement agencies a valuable tool for quickly and accurately detecting a wide array of dangerous drugs and other hazardous materials.

Explosives trace detection system DS-120E

X-ray Inspection System

X-ray inspection system BIS-X-C6580A

Hitachi's X-ray inspection systems use the penetrating power of X-rays to peer into hand luggage and cargo to detect concealed knives, explosives, and other dangerous items. Any such items hidden in parcels or carry-on bags are immediately detected in the transparent image of the package's content and using a function that differentiates and identifies different materials by color. The system is implemented as a compact box that can be installed in a tight space or conveniently added to standard conveyer type X-ray inspection systems. The system is flexible and can be readily adapted to different uses, different types of sites, and other customer needs.

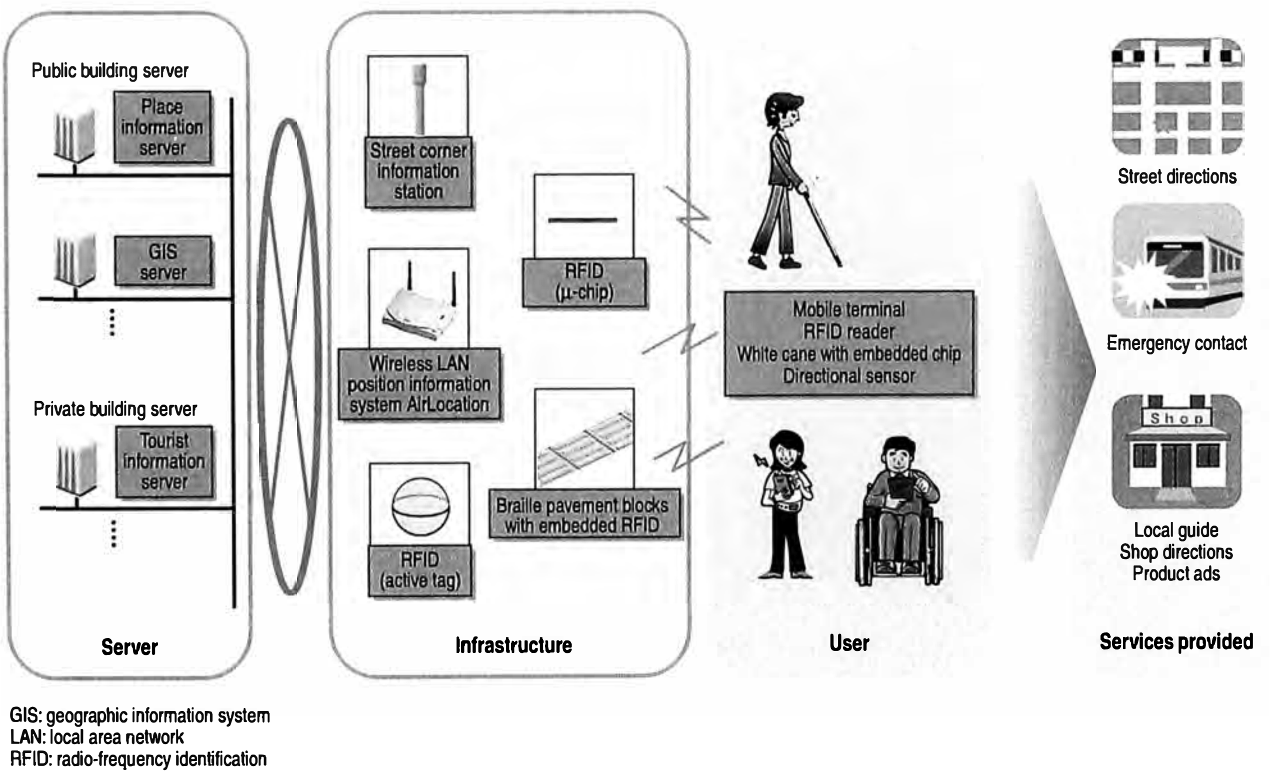
For critical infrastructure facilities calling for more advanced security screening needs, Hitachi makes a higher end X-ray CT (computerized tomography) explosives inspection system that uses tomography and is capable of measuring the material density and molecular weight of a package's content.

ITS to Assist Pedestrians: Involvement in the Free Mobility Assistance Project

The Japanese population is aging at an unprecedented rate, and by 2015 it is projected that 1 in 4 Japanese will be elderly. This demographic reality is reflected in recent legislation including the "Transportation Accessibility Improvement Law*1" and the "Accessible and Usable Building Law.*2" The ultimate objective is to achieve a "universal society" through the efforts and mutual support of the public sector, the private sector, and society at large.
In March 2004, the Ministry of Land, Infrastructure and Transport (MLIT) established the Free Mobility Assistance Project Promotion Committee to consider ways to support freer mobility by the elderly and disabled. Location information could be tied and made available at specific sites by deploying RFID devices (μ-chips or active tags) or other kinds of information devices at various places along streets. This would enable users to obtain information about these locations simply by passing near the RFID location information infrastructure or by using a local site terminal. This infrastructure would provide access to information needed to participate in society and get to work—routing information, information about public transport, and so on—to anyone, anytime, and anywhere.
2005 saw a major trial and standardization of the "Free Mobility Assistance Project" in Kobe, and in 2006 we will begin to see the infrastructure deployment and actual operation of some of the technologies evaluated in this project all across the country.

Working closely with the MLIT, Hitachi has been very much involved in the ITS (intelligent transport system) for pedestrian and has developed a number of RFID-based technologies for the visually impaired and people with other disabilities including a "routing assistance system" and an "audible warning system." Hitachi also took part in the "Play Trials" in 2004 that were part of the same "Free Mobility Assistance Project" and offered technical assessment of some of the technologies tested in this trial based on Hitachi's experience and expertise.
Hitachi remains committed to the "Free Mobility Assistance Project" through a wide range of initiatives involving RFID, the wireless LAN position information system AirLocation, deployment of a location information infrastructure that provide site-specific information to users, white canes with embedded RFID readers, directional sensors and other user terminals and peripheral equipment, servers to manage location information and provide information to user terminals. This project is now on the threshold of being extended nationwide, and Hitachi plans to integrate all these related developments into a total solution business.

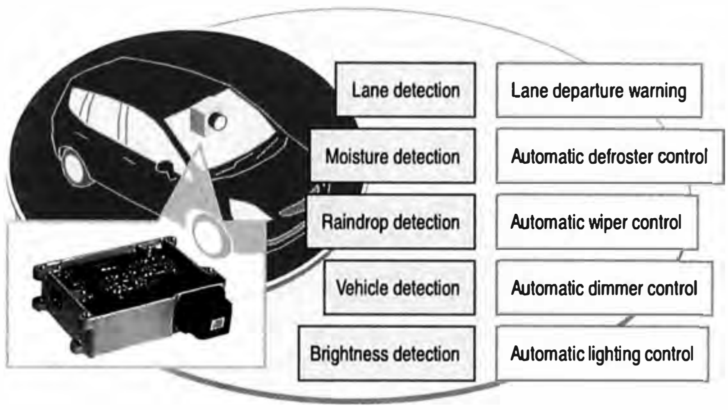
*1 Law for promoting easily accessible public transportation infrastructure of the elderly and disable persons
*2 Law for buildings accessible to and usable by the elderly and physically disable persons



Overview of the free mobility assistance system

Multifunctional Image Processing Camera

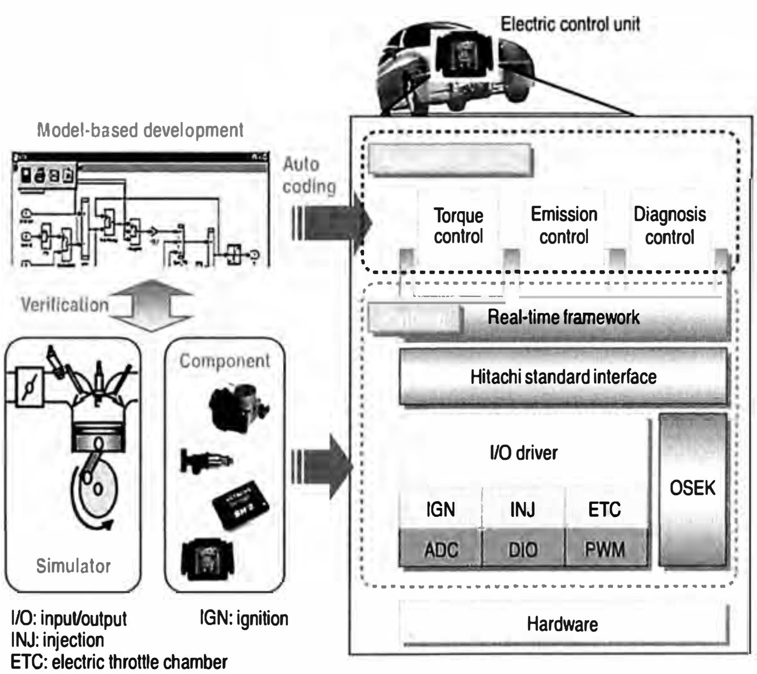
An environment recognition sensor is needed for a drive control system and a drive support system for vehicles, one that recognizes information on the surrounding environment such as traffic lanes, obstacles, the approach of other vehicles, and the weather, among other things.
The functions and circuit composition of an image processing camera that was used as an environment recognition sensor were restructured, and a multifunctional image processing camera was developed. It is faster, cheaper, and smaller than the original. The main product features are various kinds of detection software including lane detection and multitask software executive control management. Product reliability will be checked with an eye towards commercialization. New detection software will be developed.



Externals and various functions of multifunctional image processing camera

Embedded Software Technology for Vehicles

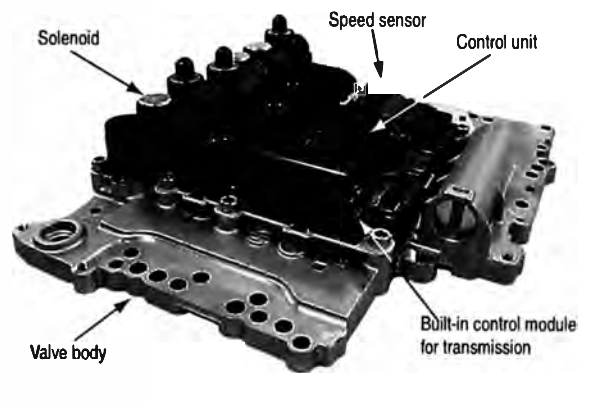
Embedded software technology for vehicles—following the continuing tendency to increase added value (environment and safety)—is getting larger in scale and more complex every year. As a result, aiming to improve software quality, Hitachi has restructured embedded processes and software architectures. As regards embedded processes, codes are automatically generated from control models designed by control development, and an embedded process was established. In regards to software architecture, by componentization and hierarchization of software for all functions, independence and interchangeability efficiency are improved. With this technology, it has become possible to promptly provide high-quality software.



I/O: input/output IGN: ignition
INJ: injection
ETC: electric throttle chamber
ADC: analog-to-digital converter
DIO: digital input and output PWM: pulse width modulation
OSEK: Offene Systeme und Deren Shcnittstellen für die Elektronik im Kraftfahrzeug (open systems and the corresponding interfaces for automotive electronics)

Structure of embedded software

Built-in Control Module for Transmissions



Built-in control module for transmissions

In recent years, automotive parts have increasingly been modularized to improve performance and reduce cost. For transmission systems, automatic transmission control modules composed of integrated mechanical components and electronic parts are appearing on the market. This type of transmission control module is described as built-in.

Hitachi has developed a built-in control module for transmissions that can be used in harsh environments, and is currently mass-producing this module. The electronic parts of the control unit are mounted on a ceramic substrate and subsequently sealed using a transfer mold to withstand the high-temperature oil inside a transmission. Peripheral sensors and actuators have been integrated by using a wiring plate.

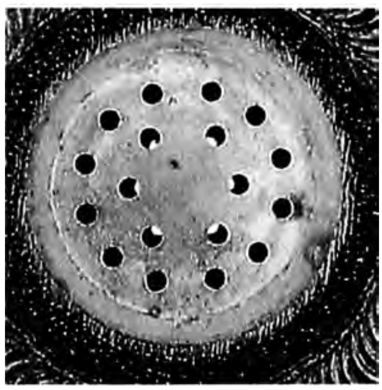
Compact Fuel Injection Valve for Vehicle Gasoline Engines

Highly accurate air-fuel ratio control is needed to comply with environmental regulations, which are becoming increasingly stringent. To meet this demand, a compact fuel injection valve has been developed.

The number of parts has been reduced by using piping material made of deep-drawing stainless material, and the weight has been reduced by optimizing the magnetic circuit. The fuel is atomized using a multi-hole nozzle and fluid analysis.

These technologies reduce exhaust gases such as hydrocarbons.

(a) Compact fuel injection valve



(b) Multi-hole nozzle

(c) Atomization of fuel

Compact fuel injection valve for vehicle gasoline engines

New Type of ABS Developed

A new type of ABS (antilock brake system), which was developed to have increased mountability for vehicles and competitive cost, is among the world's lightest and smallest in terms of onboard projection area (14% less than a competing product) due to its enhanced design.
[Main design factors]
(1) Cutting time reduced by changing to precision cold forging
(2) Number of electronic parts reduced by adopting a new custom IC
(3) Electromagnetic valve size decreased by reviewing functional allocation for each component
(4) Motor made more compact by using precision stamping technology
Similar specs to those of a high-functionality system will be adopted to improve competitiveness in the future.

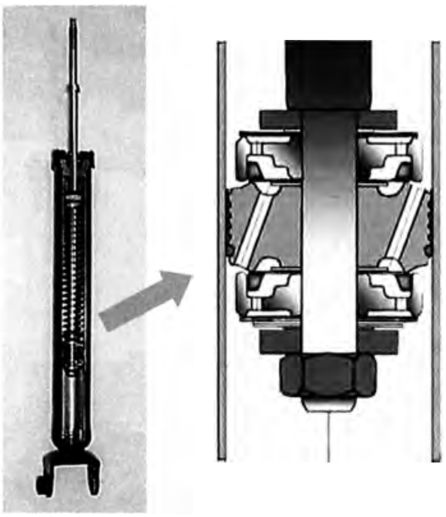
New type of low-cost ABS that is among the world's lightest and smallest

Aluminum Rear Caliper with Built-in Parking Brake Function for Toyota Motor Corporation

Aluminum rear caliper for high gas mileage and utility

The weight of the rear caliper integrated into a conventional parking brake was reduced by changing the material of cylinder body from cast iron to aluminum. (18% lighter than a cast-iron product).
[Main features]
(1) Superior operability of parking brake with ball & ramp mechanism
(2) Easier vehicle installation due to compact design
The application of this product is expanding to mid-size cars.

Dual Flow Path Shock Absorber



Dual Flow Path Shock Absorber

Electronically controlled suspension systems are becoming more common because they are required to provide exceptional handling and smooth rides in luxury automobiles. However, these systems have limited applications because they increase weight, thus increasing costs and decreasing gas mileage.
We developed an inexpensive valve mechanism that provides exceptional handling and smooth rides by adding a suitable damping property to a conventional shock absorber. This Dual Flow Path Shock Absorber* is used in the Nissan Fuga/Infiniti M35/45, which was released in Sept. 2004, and is expected to be used more widely in the future.

* See "Trademarks" on page 94.

Car Navigation System for Japan, Europe, and North America

Xanavi Informatics Corporation has developed a new car navigation system to be mounted in Nissan vehicles (for Japan, Europe, and North America) and Renault vehicles (for Europe). The system has unique switch and menu designs that suit both companies' brand identities while maintaining a shared concept. Xanavi Informatics Corporation won the Global Innovation Award from Nissan Motor Co., Ltd. for this car navigation system with high-level performance and strong competitiveness that provides functions such as Bluetooth* and traffic information with accurate route guidance and clear visibility.
(Xanavi Informatics Corporation)

* See "Trademarks" on page 94.

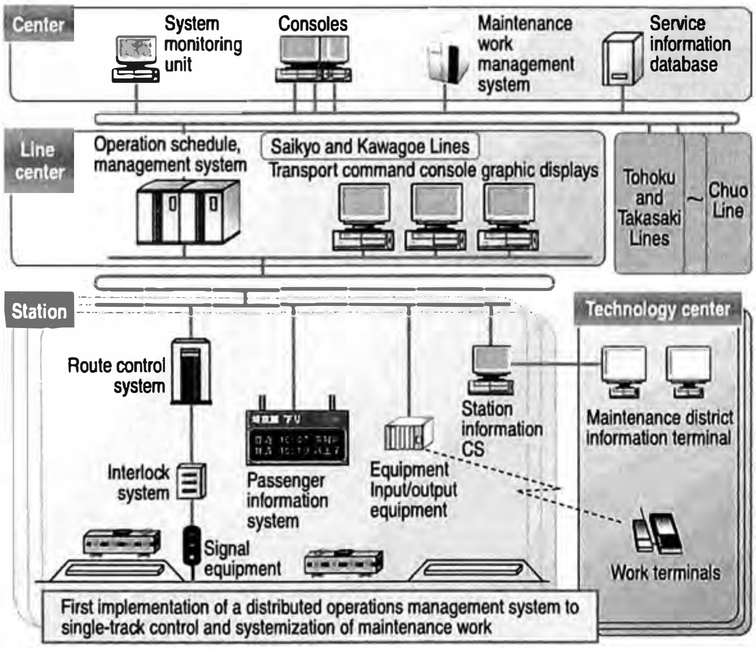
Navigation system in Nissan Fuga

Next-generation Bullet-train Cars for Central Japan Railway's Tokaido and Sanyo Shinkansen Lines

Four next-generation bullet-train cars are now being tested and evaluated in a 16-car train set operating on the Tokaido and Sanyo Shinkansen Lines. Some of the key features that will be adopted extensively on future railcars include a body tilting system enabling the cars to navigate curves at higher speed, a semi-active vibration control device enabling a smoother, more comfortable ride, and a sleek aluminum double-skin carbody that effectively muffles exterior noise.
Other innovations include a longer tapered nose called the aero double-wing that minimizes micro-pressure waves in tunnel sections, and a new-type of hood that entirely covers the vestibule spaces between cars, thus smoothing the exterior of the train and reducing exterior noise. These enhancements significantly reduce the running resistance of the new bullet-train cars and help the environment by conserving energy.

Next-generation bullet-train cars for the Tokaido and Sanyo Shinkansen lines

Operations Management System for the East Japan Railway Company's Saikyo Line



CS: communication server

Schematic overview of the ATOS

The ATOS (autonomous decentralized transport operation control system) was deployed on the Saikyo Line of the East Japan Railway Company between Osaki and Komagawa on July 31, 2005.
The system brings a number of new capabilities to the line including improved train route control on a traditionally high-density route, enhanced passenger information services when the trains get ahead or behind schedule, better systemization of maintenance work, and the first implementation of the distributed operations management system to single-track control on the line between Nisshincho and Komagawa. The system also improves operations on sections shared with the Shonan Shinjuku Line and other lines. The ATOS is scheduled for deployment on the Nambu Line in 2006.

Subway Cars of Tokyo Metro Company's Tozai Line

New subway cars employing a unique aluminum double-skin structure are now operating on the Tokyo Metro Co., Ltd's Tozai Line. Based on a radically new assembly method, the cars feature a precision, high-quality aluminum double-skin body constructed by FSW (friction-stir welding), fully self-supporting interior modules, and an integral hollow extruded mounting rail to which the modules are fastened. The assembly is further streamlined by implementing component subsystems as generic modules and curved-surface process machining.
To lessen the environmental impact, a single alloy of aluminum is used in the double-skin structure that facilitates eventual recycling of the decommissioned cars.

New subway cars for Tokyo Metro Company's Tozai Line

Digital ATC System on the Toei Shinjuku Line

(a)

(b)

Signal equipment on the Toei Shinjuku Line of Bureau of Transportation, Tokyo Metropolitan Government was completely upgraded in May 2005 for the first time since the popular line opened to the public in 1978. Adoption of Hitachi's digital ATC (automatic train control) system permits optimum one-step brake control reflecting the performance of each type of train, and this permits reduced travel times between stations. The system also implements a slight easing of brake pressure when brakes are first applied and just before the train comes to stop, which enables a smoother more comfortable ride. Compared to earlier analog systems, the new digital system requires far fewer ground equipment installations and far simpler maintenance procedures. While continuing to promote even closer coordination among ground, onboard, and other relevant equipment, Hitachi remains committed to the development and deployment of more flexible systems enabling faster travel times and reduced train headways.

Digital ATC system on Toei Shinjuku Line Series 10-300 trains:
train with onboard digital ATC equipment (a), and ground equipment (b)

Next-generation Elevator Group Control System Using Advanced Forecasting Trajectory Technique

In major cities throughout Asia, more and more high-rise buildings and large-scale multipurpose buildings are being constructed to enhance the utility of the buildings. Elevator group control systems are widely applied to efficiently operate the multiple elevators in such buildings.

Since the 1950s, Hitachi has continuously released advanced elevator group control systems, such as an instantaneous call allocation system in 1972 that informs an allocated car as soon as a new hall call is registered and a floor-attribute control system in 1997 that can change the control setting according to individual floor situations. Furthermore, a system that controls the future trajectories of elevator cars has been developed recently to reduce passenger waiting time in heavy traffic situations.

Conventional group controllers operate elevators based on past and current system situations. Consequently, in heavy traffic conditions, cars are frequently operated in a bunch, and that causes long waiting times. In contrast, the new system forecasts reference trajectories of elevator cars; the control concept is called the AFTT (advanced forecasting trajectory technique), and it aims to operate elevator cars at equal time intervals. As a result, the system can minimize long waiting times by preventing bunched operation of the cars.

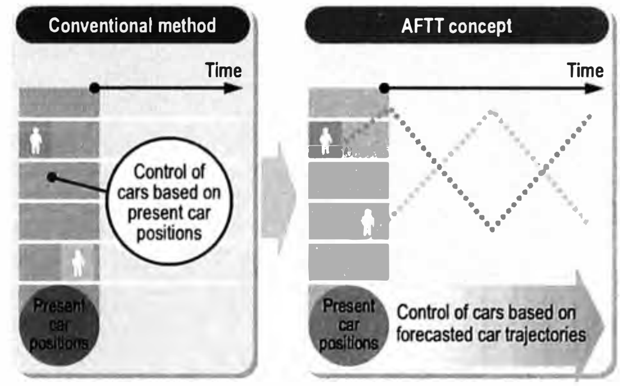
The AFTT concept is outlined as follows.

(1) Reference trajectories of cars are computed that lead the cars toward positions at equal time intervals in the near future.

(2) Forecasted trajectories of cars are computed if a new hall call occurs.

(3) The difference between the reference trajectory and the forecasted trajectory is calculated based on the area between the two trajectories.

(4) A hall call is allocated to the car that minimizes the evaluation value calculated using the above difference.

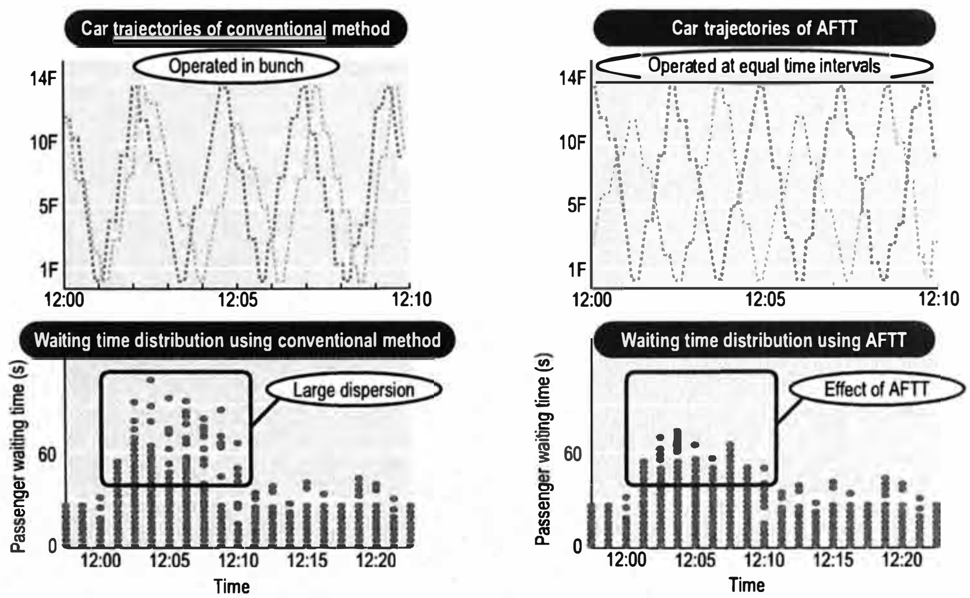


Concept of AFTT

Based on the AFTT concept, an implementation algorithm suitable for a microprocessor has been developed.

Results of simulating the AFTT implementation algorithm show that it performs better than the conventional method in heavy traffic situations. For instance, the ratio of passengers whose waiting time exceeds 60 seconds is 12% less using the AFTT than using the conventional method, and the average waiting time of the AFTT is 10% less. In addition, the trajectories of cars simulated using the AFTT algorithm show that the cars are operated at equal time intervals; on the other hand, trajectories of cars simulated using the conventional method show that the cars are operated in a bunch.

The AFTT-based elevator group control system will provide more efficient and comfortable transport of passengers than conventional systems.



Images of AFTT effect

"IT Condominium" Security System Finds Acceptance in the Chinese Market

Based on a strong favorable response in Japan, the "IT Condominium" security system was made available in China in March 2005 and adopted in THE COSMOS high-rise condominium development in Guangzhou, Guangdong Province.
Security in the common areas of THE COSMOS buildings is significantly improved by synchronizing the resident IC cards with the elevators.
Other services provided by the Hitachi Security Office include reissuing of IC cards and intrusion notification by cell phone so residents feel safe and secure in their homes.

Rendering of THE COSMOS condominium development
(Courtesy of K WORTH GROUP)

22 Sets of Moving Walkways for Central Japan International Airport

Moving walkways

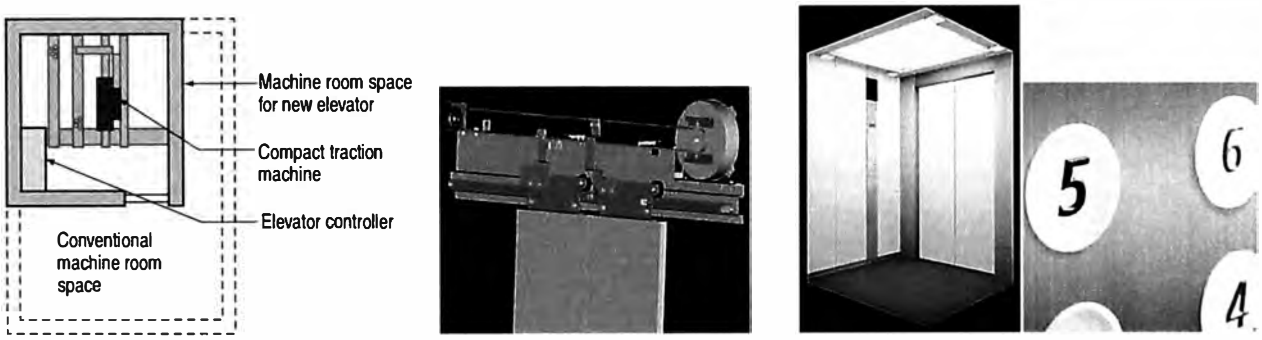
In 2005 February, the terminal building opened at the Central Japan International Airport (Centrair). Hitachi had installed 22 sets of moving walkways including 4 sets of a wide type called S1600 (effecive step width: 1,600 mm, effective balustrade width: 1,800 mm), which were the first installed in Japan. Centrair is located on the sea on a causeway over Ise bay and 35 km from central Nagoya. It has features of universal design.

[Main features]

(1) Wheelchair parallel accessibility
(2) Audio guidance
(3) Minimized difference in level at entrance
(4) Eye-friendly colored-steps
(5) Braking system preventing falling accidents

New Mini Machine Room Elevator

A mini machine room elevator has been developed for the world market.
[Main features]
(1) Compact mini machine room
he new mini machine room elevator uses a compact gearless achine, which enables dramatically reducing machine room ace, and the machine room floor area required is only the size of the hoistway.
(2) Slim door machine
A slim door machine is used that is equipped with an especially slim permanent magnetic motor that does not interfere with the car ceiling, even if a decorated ceiling is used and the car height exceeds the standard.
(3) New interior car and operation panel design
The design of the interior car of the new mini machine room elevator, which includes high-contrast convex character buttons, was developed to facilitate the use of the elevator by the elderly and handicapped.

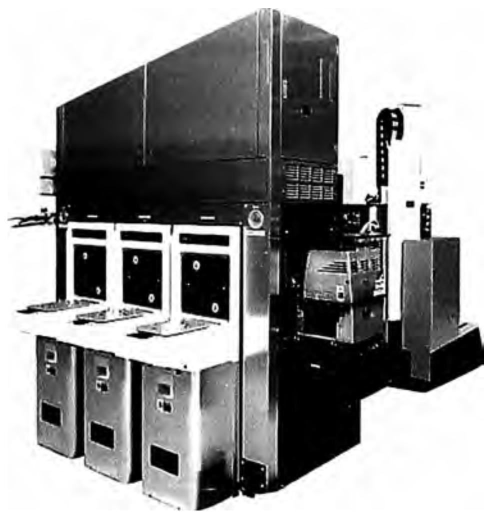


(a) Machine room layout design (b) Appearance of slim door machine (c) Interior car design and convex buttons

New mini machine room elevator

New Dielectric Etching System: U-8250

Hitachi has now launched U-8250, a new etching system that supports 45-nm node dielectric film processing. Building on the proven capabilities of ECR (electron cyclotron resonance) plasma etching technology, the U-8250 combines excellent microfabrication capabilities with stable operation.
[Main features]
(1) Enhanced plasma and wafer ion implantation control capabilities covering a wide range of dielectric film materials
(2) Improved CoO (cost of ownership) for implementing reactors that support particle-less and lower contamination processing
(Hitachi High-Technologies Corporation)



New dielectric film etching system: U-8250

High-resolution, High-speed Dark-field Wafer-inspection System: IS3000 for 45-nm Node Devices

Equipment and processes on 300-mm wafer fab lines introduce a range of microdefects for a variety of reasons, and these defects can drag down the yield of the fab line. For this reason it is essential to sensitively monitor as many wafers as possible, rapidly identify the causes of defects, and quickly remedy the problems.
Exploiting recent advances in dark-field imaging technology, we have now developed the dark-field wafer inspection system IS3000 combining high resolution with high speed that can be applied to mass production 45-nm node micro-device fab lines.

[Main features]

(1) A high-resolution dark-field imaging optical system that permits both high resolution together with high speed inspection
(2) Supports a high throughput of up to 35 wafers per hour (300-mm wafers).
(3) Capable of generating condition setting recipes very quickly
(4) A variety of built-in defect analysis capabilities

(Hitachi High-Technologies Corporation)

High-resolution, high-speed dark-field wafer-inspection system: IS3000

DesignGauge: Semiconductor Pattern Measurement System Based on Design Information

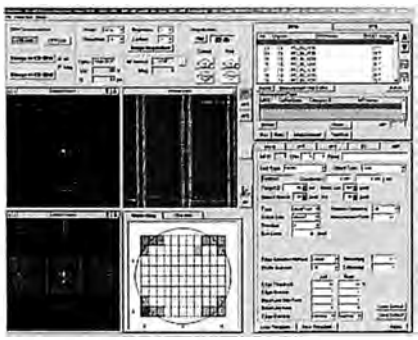
As semiconductor process technology evolves toward smaller features, it becomes increasingly difficult to form submicron patterns in accordance with CAD data. This led to our recent development of DesignGauge, a new measurement system that uses design information to evaluate and compare patterns with CAD data. DesignGauge is software that runs on a PC connected to a metrology SEM (scanning electron microscope) over a network.

[Main features]

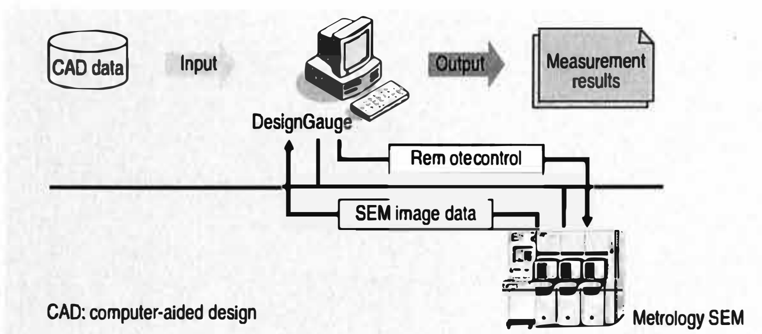
(1) Generates recipes off-line.
(2) Can be operated by remote control.
(3) Uses CAD data to perform a range of measurement functions.
(4) Remeasuring capabilities

Extending these capabilities to compare actual patterns against CAD data, we plan to develop 2-dimensional measurement technology using CAD data to further improve the value-added capabilities of metrology SEM.

(Hitachi High-Technologies Corporation)



(a)



(b)

DesignGauge screen shot (a) and system configuration (b)

High-sensitivity High-speed SEM Visual Inspection System: I-6300 for Next-generation Semiconductor Devices

Hitachi has now developed the visual inspection system I-6300, a high-sensitivity high-speed tool for application to 45-nm node and beyond next-generation semiconductor device fabrication.

As minimum device dimensions decrease and device layers increase, the ability to achieve reasonably fast throughput becomes more problematic for SEM (scanning electron microscope)-based inspection tools that have the sensitivity and potential contrast necessary to resolve such fine features. The I-6300 meets this challenge with an all-new electron-optical system and innovative high-speed image processing to achieve a threefold improvement in throughput compared to the previous visual inspection system, and also provides better detection sensitivity and repeatability.

[Main features]

(1) Featuring a new electron-optical system and fast image processing technology, the I-6300 offers much better sensitivity and faster visual inspection capabilities.

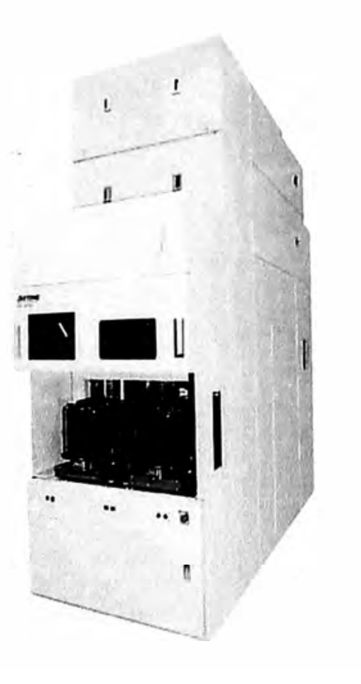
(2) A new type of electrode supports improved potential contrast detection sensitivity and repeatability.

(3) An improved recipe generation support tool makes it easier to create recipes and reduces the recipe set-up time.

(Hitachi High-Technologies Corporation)

High-sensitivity high-speed SEM visual inspection system: I-6300

Vertical Ultrahigh-temperature Annealer



Vertical ultrahigh-temperature annealer

We have developed a vertical ultrahigh-temperature annealer for batch processing of 300-mm wafers. Developed over a three-year period beginning in 2002, the annealer was one of the advanced semiconductor device process equipment initiative projects supported by NEDO (New Energy and Industrial Technology Development Organization). A number of new technologies emerged in the process of developing the state-of-the-art annealer including a new heating technology that exceeds 1,350°C needed in the SIMOX (separation by implanted oxygen) wafer annealing process, a novel temperature control scheme, technology for reducing crystalline defects, and new technology for reducing metal contamination.

[Main features]

(1) High throughput: the vertical batch annealer features an automatic wafer transport mechanism that permits processing of up to 75 wafers in a single batch.

(2) Precision temperature control: ramping up the temperature is precisely controlled in 1°C increments up to a maximum processing temperature of 1,400°C, well above 1,350°C needed for SIMOX wafer annealing.

(3) Precision processing: (a) crystalline defects and slip line propagation in the batch processing is avoided. (b) metal contamination is significantly reduced to less than 5×10^{10} atms/cm^2. (c) uniformity of the oxidation layer thickness between batches is reduced to less than 0.2%.

(Hitachi Kokusai Electric Inc.)

Module Assembly System AL/AB6000 Series for Wide-screen TVs

We have developed a module assembly system supporting automated assembly lines for wide-screen TVs up to 47 inches that integrates the entire sequence from TAB (tape automated bonding) mounting to connection of printed circuit boards and resin coating.

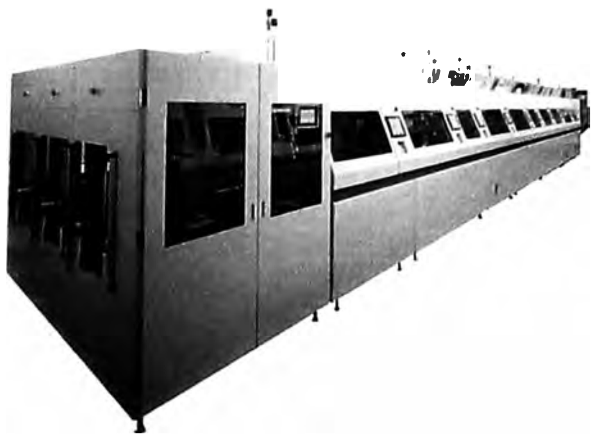
[Main features]

(1) High production level: achieves high-speed line tact of 25 seconds when mounting 14 TABs on two sides of the current most prevalent 32-inch wide-screen panels.

(2) Ensures excellent manufacturing flexibility: (a) various units and buffers can be freely assembled to accommodate any combination of manufacturing line processes and tact times. (b) the AL/AB6000 series can accommodate a wide range of wide-screen panel sizes from 27 inches to 47 inches.

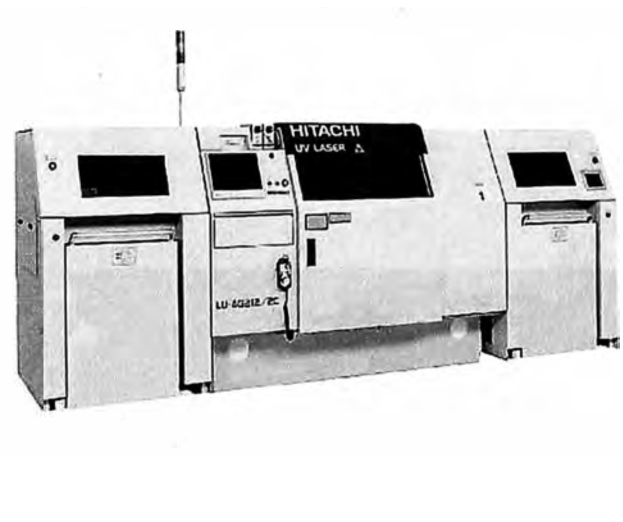
(3) High availability: supports automatic switching of TAB tape, ACF (anisotropic conductive film) tape, and other basic materials, to enable long continuous operation of the line.

(Hitachi High-Technologies Corporation)



Module assembly system AL/AB6000 series for wide-screen TVs

Two-panel, Four-beam UV Laser Drilling Machine



Four-beam UV laser drilling machine, LU-4G212, that drills two panels simultaneously using four beams scanned by 2,000-hole/s galvanometer scanners

Printed wiring board production is growing due to increasing demands for mobile phones, digital cameras, PCs, digital audio-visual equipment, etc. These compact and multi-functional pieces of electronic equipment and components require higher-density wiring with small via-holes. To meet these demands, a four-beam UV (ultraviolet)-laser drilling machine, LU-4G212, was developed.

[Main features]

(1) An optical system was developed that splits a UV laser beam generated by a high-speed, high-power LD (laser diode)-pumped UV pulse laser into four beams and thus processes two panels at a time with two beams. The optical system can produce beams with both top-hat-shaped and Gaussian beam profiles for resin direct micro-via-hole drilling.

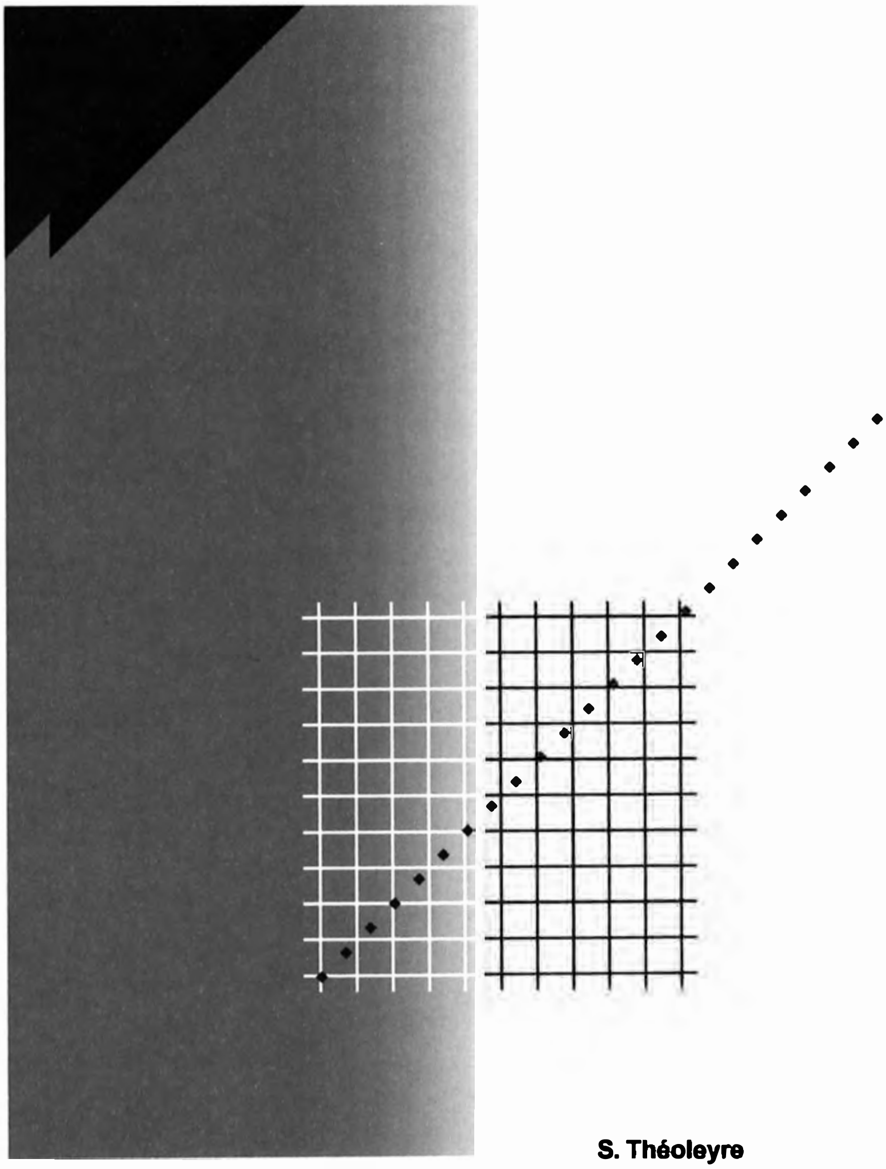
(2) An original galvanometer scanner is used that has a design optimized for the rotor dynamics and cooling system operated at a 2,000-hole/s maximum drilling speed. The combination of the four-beam system and the new galvanometer scanner increases drilling productivity by 70% compared to a conventional two-beam system.

ANEXO H

TÉCNICAS DE INTERRUPCIÓN EN MEDIA TENSIÓN-SCHENEIDER

Cahier technique no. 193

MV breaking techniques



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no. 193

MV breaking techniques

Serge THEOLEYRE

Dr. Theoleyre joined Schneider Electric in 1984 after having obtained a Doctorate in Engineering from the "Ecole Nationale Supérieure d'Ingénieurs Electriciens" in Grenoble in 1983. Initially he took charge of research and development and then marketing for the Power Capacitor activity.
Since 1995, he has been responsible for Schneider Electric's actions in the fields of standardization and technical communication within the Transmission and Distribution Business sector (HV/MV).

ECT 193 first issue, June 1999

Lexicon

Breaking Capacity:
A presumed current value that a switching device must be capable of breaking under the recommended conditions of use and behavior.

Earthing fault:
Fault due to the direct or indirect contact of a conductor with the earth or the reduction of its insulation resistance to earth below a specified value.

Fault:
Accidental modification affecting normal operation.

I_r:
Rated current corresponding to the rms. value of the current that the device must be capable of withstanding indefinitely under the recommended conditions of use and operation.

Isc:
Short-circuit current.

Overvoltage:
Any voltage between a phase conductor and the earth or two neutral phase conductors where the peak value exceeds the highest voltage acceptable for the equipment.

Overvoltage factor:
Ratio between the overvoltages' peak value and the peak value of the maximum voltage acceptable by the device.

Rated value:
Value generally set by the manufacturer for given operating conditions for a component, a mechanism or piece of equipment.

Re-ignition:
Resumption of current between the contacts of a mechanical switching device during a breaking operation, **within** a quarter cycle after passing to 0 current.

Re-striking:
Resumption of current between the contacts of a mechanical switching device during a breaking operation, **after** a quarter cycle after passing to 0 current.

Short-circuit:
An accidental or intentional connection through a resistance or relatively low impedance, of two or more points on a circuit normally existing at different voltages.

Switching device:
Device intended to establish or interrupt current in an electrical circuit.

Switchgear:
General term applicable to switching devices and their use in combination with control, measurement, protection, and command devices with which they are associated.

Time constant for de-ionization:
Time at the end of which arc resistance will have doubled assuming that its rate of variation remains constant.

Transient recovery voltage:
Recovery voltage between the contacts of a switching device during the time where it presents an noticeable transient character.

U_r:
Rated voltage corresponding to the rms. value of the voltage that the device must be capable of withstanding indefinitely under the recommended conditions of use and operation.

MV breaking techniques

The ability to break current in an electrical circuit is essential in order to guarantee the safety of people and property in the case of faults, as well as to control the distribution and use of electrical energy.

The aim of this Cahier Technique is to detail the advantages, disadvantages and applicational fields of past and present Medium Voltage breaking techniques.

Having defined the currents to be broken and discussed breaking on a theoretical level, the author goes on to present breaking in air, oil, and in SF_6, finishing with two comparative tables.

To date, breaking using electrical arcing remains the only viable solution, whether in SF_6 or under vacuum; it requires expertise that this Cahier Technique invites you to share.

Contents

1 Introduction

Electrical energy is transmitted from the generating power station to consumer points via an electrical network (shown in **figure 1**).
It is essential to be able to interrupt the current at any point in the network in order to operate or maintain the network or to protect it when a fault occurs. It is also necessary to be able to restore current in various normal or fault situations.
In order to choose the devices intended to accomplish this task, information on the current to break and the field of application is crucial (see **fig. 2**). It can fall into one of three categories:

■ Load current, which is normally smaller than the rated current I_r. The rated current, I_r is the rms. value of current that the equipment must be capable of withstanding indefinitely under the recommended conditions of use and operation.

■ Overload current, when the current exceeds its rated value.

■ Short-circuit current, when there is a fault on the network. Its value depends on the generator, the type of fault and the impedances upstream of the circuit.

Furthermore, when opening, closing or in continuous service the device is subjected to several stresses:

■ dielectrical (voltage),
■ thermal (normal and fault currents),
■ electrodynamic (fault current),
■ mechanical.

The most important stresses are those which occur during transient operation and breaking, which are accompanied by electrical arcing phenomena. Arcing behavior is difficult to predict despite current modeling techniques.

Experience, know-how and experimentation still play a large part in designing breaking devices. They are called "electromechanical" devices, since at present static breaking in medium and high voltage is not technically and economically viable.

Of all of these breaking devices, circuit breakers are the most interesting since they are capable of making, withstanding, and breaking currents under normal and abnormal conditions (short-circuit). This Cahier Technique will mainly discuss breaking alternating current using circuit breakers.

The voltage range considered is that of Medium Voltage (1 kV - 52 kV), since it is in this voltage range that the greatest number of breaking techniques exist. The first part of the document will deal with phenomena occurring during breaking and closing. The second part presents the four most wide-spread types of breaking techniques currently used i.e. breaking in air, oil, vacuum and SF_6.

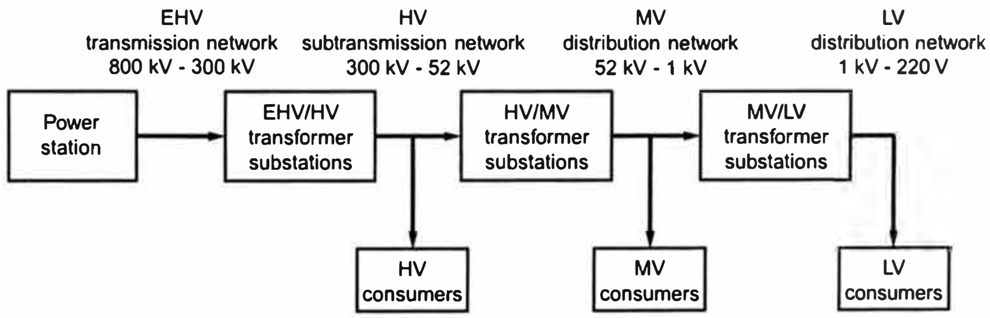


Fig. 1 : diagram of an electrical network.

	■ IEC definition ■ Function	Opening			Closing			Isolating
		○	●	⚡	○	●	⚡	
Disconnector	■ Mechanical connection device which in an open position guarantees asatisfactory isolating distance under specific conditions. ■ Intended to guarantee safe isolation of a circuit, it is often associated with an earthing switch.	yes	no	no	yes	no	yes □	yes
Earthing switch	■ Specially designed switch for connecting phase conductors to the earth. ■ Intended for safety in case of work on the circuits, it relays the de-energized active conductors to the earth.	yes	no	no	yes	no	yes □	no
Switch	■ Mechanical connection device capable of establishing, sustaining and breaking currents under normal circuit conditions eventually including overload currents in service. ■ Intended to control circuits (opening and closing), it is often intended to perform the insulating function. In public and private MV distribution networks it is frequently associated with fuses.	yes	yes	no	yes	yes	yes	yes □
Contactor	■ Mechanical connection device with a single rest position, controlled other than by hand, capable of establishing, sustaining and breaking currents under normal circuit conditions, including overvoltage conditions in service. ■ Intended to function very frequently, it is mainly used for motor control.	yes	yes	no	yes	yes	yes	no
Circuit breaker	■ Mechanical connection device capable of establishing, sustaining and breaking currents under normal circuit conditions and under specific abnormal circuit conditions such as during a short-circuit. ■ General purpose connection device. Apart from controlling the circuits it guarantees their protection against electrical faults. It is replacing contactors in the control of large MV motors.	yes	yes	yes	yes	yes	yes	no

○ = at no load ● = under load ⚡ = short-circuit □ = depending on the case

Fig. 2 : various switching devices, their functions and their applications

2 Breaking load and fault currents

2.1 Breaking principle

An ideal breaking device would be a device capable of breaking current instantaneously. However, no mechanical device is capable of breaking current without the help of electrical arcing. This phenomenon limits overvoltages and dissipates the electromagnetic energy of the electrical circuit, but it delays complete breaking of the current.

The ideal switch

Theoretically speaking, being able to break current instantaneously, it involves being able to pass directly from the state of conductor to the state of insulator. The resistance of the "ideal" switch must therefore pass immediately from zero to infinity, (see fig. 3).

This device must be capable of:

■ absorbing the electromagnetic energy accumulated in the circuit before breaking, i.e. $\frac{1}{2}$ Li^2 in case of a short-circuit due to the reactive nature of the networks;

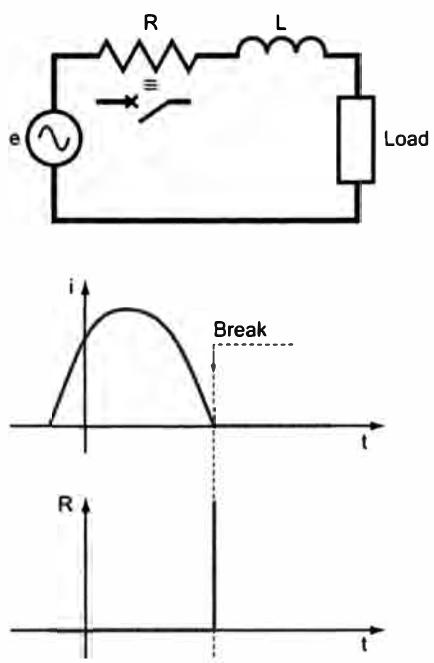


Fig. 3 : breaking by an ideal switch.

■ withstanding the overvoltage (Ldi/dt) appearing across the terminals of the device and which would have an infinite value if passing from insulator to conductor occurred in an infinitely small period of time. This would inevitably lead to dielectric breakdown.

Assuming that these problems have been eliminated and that perfect synchronization has been achieved between the natural passing of the current to 0 and the device's insulator-conductor transition, there still remains another difficult aspect to take into consideration, that of transient recovery voltage (TRV).

In fact, just after the current has been interrupted, the recovery voltage across the switch's terminals joins the network voltage which is at its maximum at this moment for reactive circuits. This occurs without an abrupt discontinuity due to the parasite capacitances of the network. An unsteady state is set up whilst the voltage comes back in line with that of the network. This voltage, called transient recovery voltage (TRV), depends on network characteristics and the rate of increase (dv/dt) of this voltage can be considerable (several kV / microsecond). To put it simply this means that to avoid breaking failure, the ideal switch must be capable of withstanding several kV less than one microsecond after the transition from conductor-insulator.

Breaking using electrical arcing

Two reasons explain the existence of electrical arcing:

■ It is practically impossible to separate the contacts exactly at the natural 0 current point due to the uncertainty in the measurement-order: for an rms. value of 10 kA, the instantaneous current 1 ms before 0 is still at 3,000 A. The instantaneous overvoltage Ldi/dt which would appear across the terminals of the device if it immediately became insulating would be infinite and lead to the immediate breakdown across the inter-contact gap which is still small.

■ Separation of the contacts must be accomplished at sufficient speed for the dielectric strength between the contacts to remain greater than the transient recovery voltage. This requires mechanical energy close to infinity, that no device can provide in practice.

The electrical arcing breaking process takes place in three phases

- □ the sustained arc phase,
- □ the arc extinction phase,
- □ the post-arcing phase.

■ Arc propagation phase

Before reaching zero current the two contacts separate causing dielectric breakdown of the inter-contact medium. The arc which appears is made up of a plasma column composed of ions and electrons from the inter-contact medium or metal vapor given off by the electrodes (see **fig. 4**). This column remains conductive as long as its temperature is maintained at a sufficiently high level. The arc is thereby "sustained" by the energy that it dissipates by the Joule effect.

The voltage which appears between the two contacts due to the arc's resistance and the surface voltage drops (cathodic and anodic voltage) is called the arcing voltage (U_a).

Its value, which depends on the nature of the arc, is influenced by the intensity of the current and by the heat exchange with the medium (walls, materials, etc.). This heat exchange which is radiative, convective and conductive is characteristic of the device's cooling capacity.

The arc voltage's role is vital since the power dissipated in the device during breaking strongly depends on it.

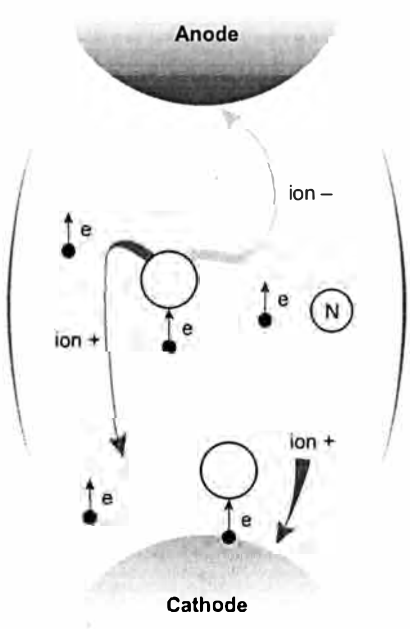


Fig. 4 : electrical arcing in a gaseous medium.

$W = \int_{t_0}^{t_{arc}} U_a \, i dt$ where t_0 is the moment of arc initiation and t_{arc} is the moment of breaking.

In medium voltage and high voltage, it always remains well below network voltages and does not therefore have a limiting effect, except in particular cases discussed further on. Breaking is therefore near the "natural" zero of the alternating current.

■ Arc extinction phase

Interrupting of the current corresponding to arc extinction is accomplished at zero current on condition that the medium quickly becomes insulating again. For this to occur, the channel of ionized molecules must be broken. The extinction process is accomplished in the following manner: near zero current, resistance to the arc increases according to a curve which mainly depends on the de-ionization time constant in the inter-contact medium (see **fig. 5**).

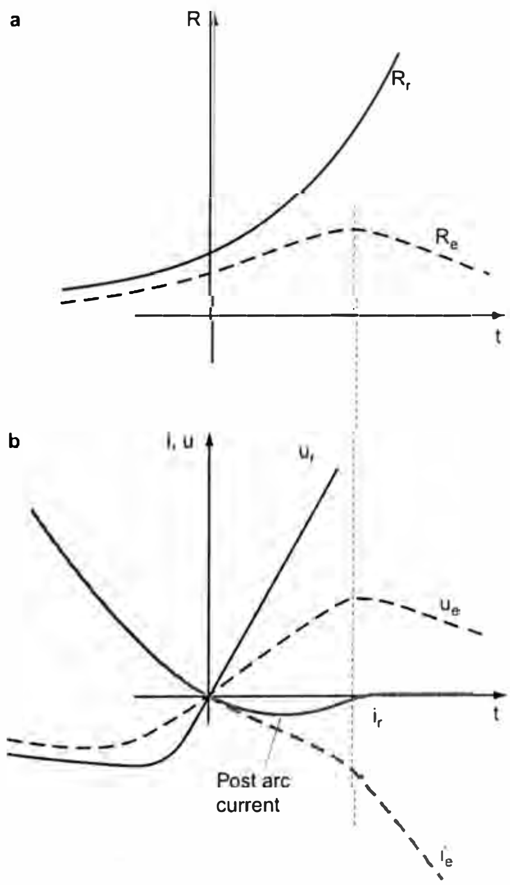


*Fig. 5 : change in arc resistance **[a]** current and voltage **[b]** during the extinction phase in case of successful breaking **(r)** or thermal failure **(e)**.*

At zero current, this resistance has a value which is not infinite and a post-arcing current once again crosses the device due to the transient recovery voltage which appears across the terminals.

If the power dissipated by the Joule effect exceeds the characteristic cooling capacity of the device, the medium no longer cools down: thermal runaway followed by another dielectric breakdown takes place: resulting in thermal failure.

If on the other hand the increase in voltage does not exceed a certain critical value, the arc's resistance can increase sufficiently quickly so that the power dissipated into the medium remains less than the cooling capacity of the device thereby avoiding thermal runaway.

■ Post-arcing phase

In order for breaking to be successful, it is also necessary for the rate of dielectric recovery to be much quicker than that of the TRV (see **fig. 6**) otherwise dielectric breakdown occurs.

At the moment when dielectric failure occurs, the medium once again becomes conductive, generating transient phenomena which will be looked at in more detail further on.

These post-breaking dielectric failures are called:

□ re-ignition if it takes place within the quarter of a period following the zero current,

□ re-striking if it takes place afterwards.

■ TRV in the standards

Even though the rate of increase of TRV has a fundamental impact of on the breaking capacities of devices, this value cannot be precisely determined for all network configurations. Standard IEC 60056 defines a TRV range for each rated voltage corresponding to the requirements normally encountered (see **fig. 7**).

The breaking capacity of a circuit breaker is therefore defined as: the highest current that it can break at its rated voltage with the corresponding rated TRV.

A circuit breaker must be capable of breaking all currents less than its breaking capacity for all TRVs whose value is less than the rated TRV value.

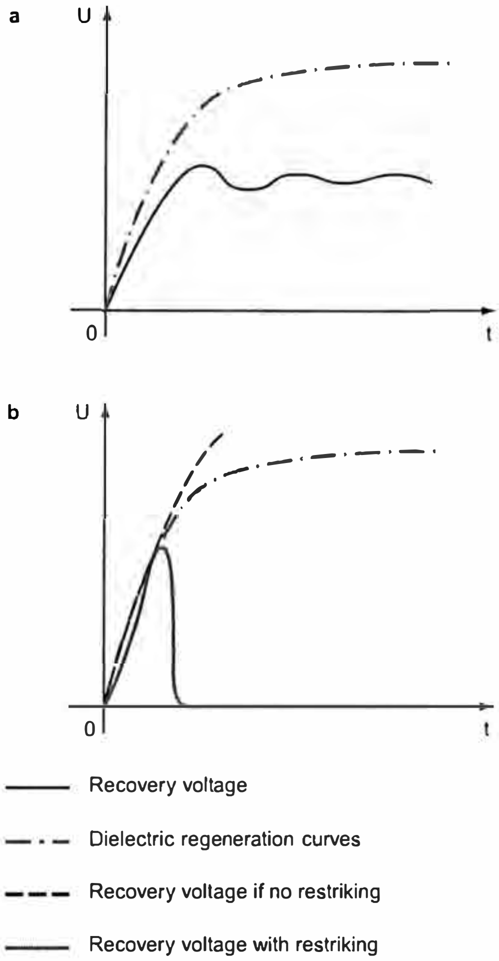


Fig. 6 : dielectric recovery curves: successful breaking [a] or dielectric failure [b].

Rated voltage (U_r in kV)	**7.2**	**12**	**17.5**	**24**	**36**	**52**
Peak TRV value (U_c in kV)	12.3	20.6	30	41	62	89
Time t_3 (in µs)	52	60	72	88	108	132
Rate of increase (U_c / t_3)	0.24	0.34	0.42	0.47	0.57	0.68

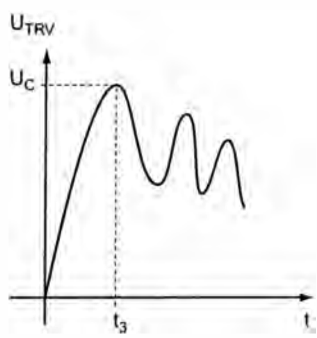


Fig. 7 : rated transient recovery voltage in the case of a short-circuit across the terminals of a circuit breaker (§ 4.102 IEC standard 60056).

2.2 Breaking load currents

Under normal operation, in MV, circuit breaking occurs:

■ with a load current from a few to a few hundred amperes, a low value relative to the short-circuit current (from 10 to 50 kA);

■ with a power factor greater than or equal to 0.8. The phase shift between the electrical circuit voltage and the current is small and the minimum voltage occurs around the current's minimum (highly resistant circuit).

The voltage across the terminals of the breaking device is established while network voltage is practically without any transient phenomena (see fig. 8).
Under such conditions, breaking generally occurs without any problems since the device is dimensioned for high currents in quadrature with the voltage.

Breaking inductive currents

■ Current chopping
Breaking inductive currents can give rise to overvoltages caused by early breaking of the current, otherwise known as "current chopping" phenomena.
For low inductive currents (from a few amperes to a several dozens of amperes), the cooling capacity of the devices dimensioned for the short-circuit current is much higher in relation to the energy dissipated in the arc. This leads to arc instability and an oscillating phenomena occurs which is "seen" by the breaking device and the inductances (see fig. 9 and fig. 10). During this high frequency oscillation (of around 1 MHz) passing to zero current is possible and the circuit breaker can interrupt the current before it passes to its natural zero at the industrial frequency (50 Hz).

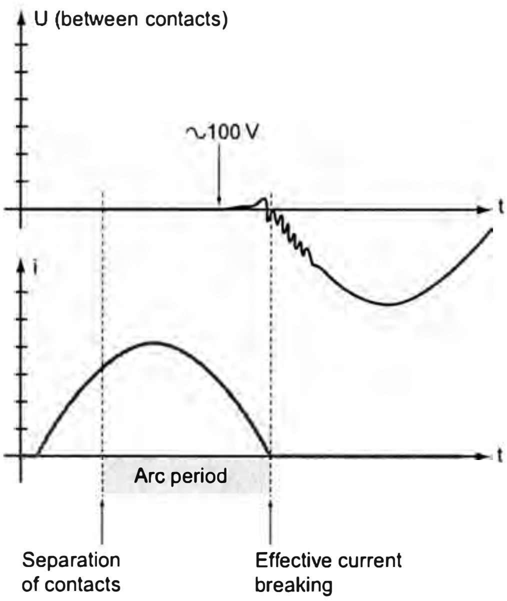
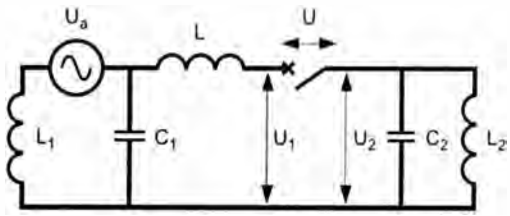
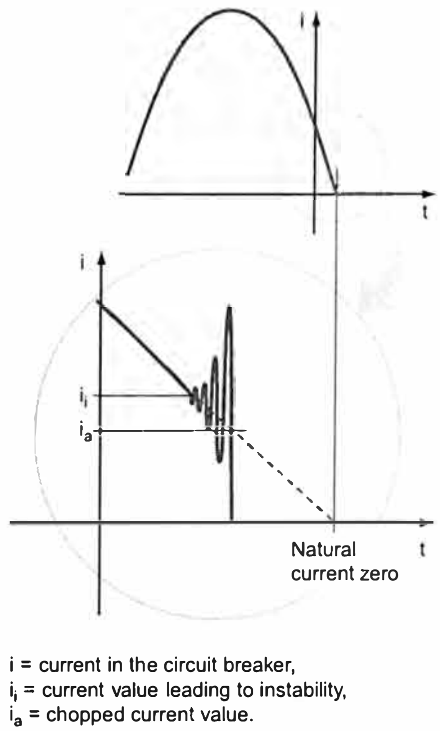


Fig. 8 : there are very few transient phenomena during the breaking of a resistive load current.



L_1 , C_1 = upstream inductance and capacity (supply source),
L_2 , C_2 = downstream inductance and capacity (transformer primary),
L = connection inductance downstream of circuit breaker D (busbars or cables).

Fig. 9 : diagram of the circuit on breaking a low inductive current.



i = current in the circuit breaker,
i_i = current value leading to instability,
i_a = chopped current value.

Fig. 10 : high frequency oscillating phenomena or "current chopping" on breaking an inductive current.

This phenomenon, called "current chopping", is accompanied by a transient overvoltage mainly due to the oscillatory state which is set up on the load side (see **fig. 11**).
The maximum value of the overvoltage (U_{Cmax}) on the load side is given by the following equation:

$$U_{Cmax}^2 = u_a^2 + \left[\frac{\eta_m L_2 i_a^2}{C_2}\right]$$

in which:
u_a = chopping voltage,
i_a = chopping current,
η_m = magnetic efficiency.

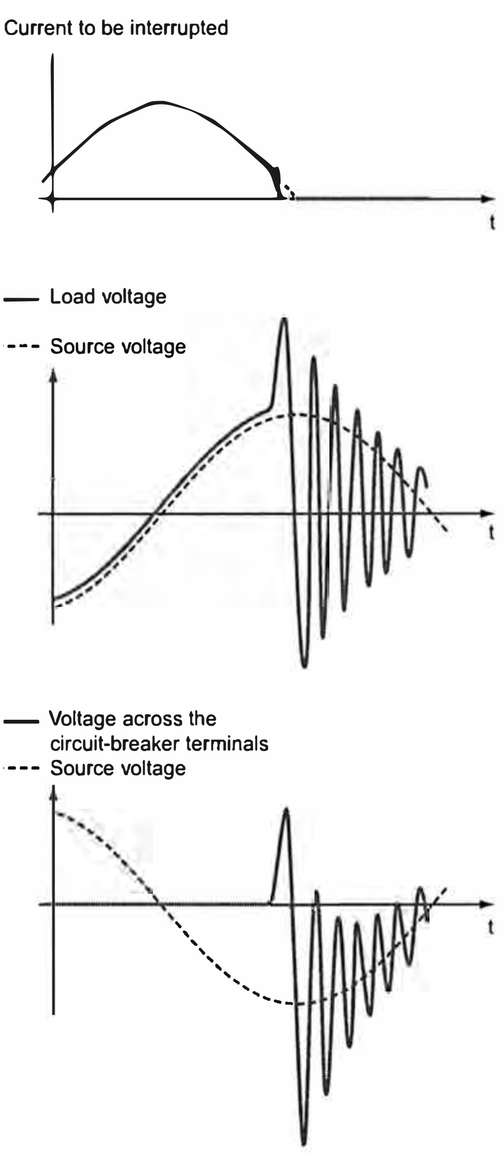


Fig. 11 : voltage and current curves at the time of breaking low inductive currents.

On the supply side, the voltage value is equal to the value of the chopping voltage tending towards the network voltage, Un with an oscillating state depending on C1 and L1. The voltage value between the contacts of the circuit breaker is equal to the difference between these two voltages.
These equations clearly show the influence of the network's characteristics, bearing in mind that the chopping current depends strongly on C1 and on the concerned device.

■ Re-ignition

Another phenomena can lead to high overvoltages. It is re-ignition during opening. Generally speaking, re-ignition is inevitable for short arcing periods since the distance between contacts is not sufficient to withstand the voltage which appears across the terminals of the device. This is the case each time an arc appears just before the current passes to natural zero.
The voltage on the load side rejoins the voltage on the supply side with an unsteady state oscillating at high frequency (around 1 MHz). The peak value of the oscillation, determined by the load voltage of the downstream parasite capacitances is therefore twice the preceding value.
If the circuit breaker is capable of breaking high frequency currents, it will manage to break the current the first time it passes to zero a few microseconds after re-ignition. Re-ignition is very likely to reoccur due to the increase in the amplitude of oscillation and the phenomena is repeated causing an escalation in voltage which can be dangerous for the load
(see Cahier Technique no. 143).
It should be noted that the same phenomena appears during device closure: it causes pre-striking when the contacts are brought sufficiently close together. As in cases of successive re-ignition, the stored energy increases at each breaking attempt but the voltage increase is limited by the bringing together of the contacts.

■ Field of application

In Medium Voltage this involves the magnetizing currents of transformers under no load or low load, motors and shunt inductances.

□ Transformers under no load or low load

Transformers can be operated under low load conditions (e.g. at night) for network management requirements. The currents corresponding to their magnetizing currents vary from a few amperes to several dozens of amperes and their chopping factor can be very high. However, even if the current is chopped at its peak value, the possible overvoltage factors are generally low taking into account the capacitances and the inductances involved.

In overhead distribution, the risk related to the appearance of overvoltage current is even lower since it is limited by lightning arrestors. Furthermore, standards relating to transformers define impulse wave tests which confirm their capacity to withstand operational overvoltages.

□ Shunt inductances

These inductances are used to compensate for the reactive component of the lines or to avoid increases in voltage on very long lines with low loads. They are most often used in HV but can also be used in MV.

Breaking overvoltages generally remain below an overvoltage factor of 2.5 due to the impedances involved. If there is a risk that the breaking overvoltage will exceed this limit, lightning arrestors and breaking resistors are connected in parallel with the circuit breaker.

□ Motors

Stator and rotor windings of motors are so that the current absorbed under no load conditions by these motors as well as the start-up currents are basically inductive. Given the great number of switching operations, overvoltages occur very often and can become critical because of the progressive deterioration in the insulation that they engender, in particular if opening occurs during the start-up phases.

As a general rule, circuit breakers must be chosen that do not re-strike or that have a low probability of re-striking. Otherwise, R-C systems can also be placed across the motor's terminals in order to deviate high frequency transient currents or ZnO type voltage limiting systems.

■ Breaking inductive currents and the standards.

International standards do not exist regarding the breaking of inductive currents, however IEC technical report 61233 stipulates tests for circuit breakers used to supply the motors and shunt inductances.

□ Motors

For circuit breakers with rated voltages between 1 kV and 17.5 kV, a standardized circuit simulating a blocked motor is specified for laboratory tests.

□ Shunt inductances

They are not very wide-spread in MV, nevertheless, they are sometimes used in 36 kV. The tests carried out in a laboratory are solely defined for three phase circuits with a rated voltage greater than 12 kV.

Breaking capacitive currents

Breaking capacitive currents can cause to overvoltages due to re-striking during the voltage recovery phase.

■ In theory, capacitive currents can be broken without any difficulty. In fact, when the device interrupts the current, the voltage across the terminals of the generator is at its maximum since the current and the voltage are out of phase by $\pi/2$; since the capacitor remains charged at this value after current breaking, the voltage across the terminals of the switch, initially at 0, slowly increases without TRV and with a derivative in relation to time (dv/dt) equal to zero at the origin.

■ On the other hand re-striking problems are difficult. In fact, after a 1/2-period, the network voltage is reversed and the voltage across the terminals of the switch reaches twice the peak value. The risk of re-striking between the contacts is therefore increased and this is proportional to the slowness of opening.

If there is re-striking at peak voltage, the capacitor is discharged in the circuit's inductance creating an oscillating current with a peak voltage of 3 (see **fig. 12**). If breaking is effective at the following zero current, the capacitor remains charged at a voltage of 3.

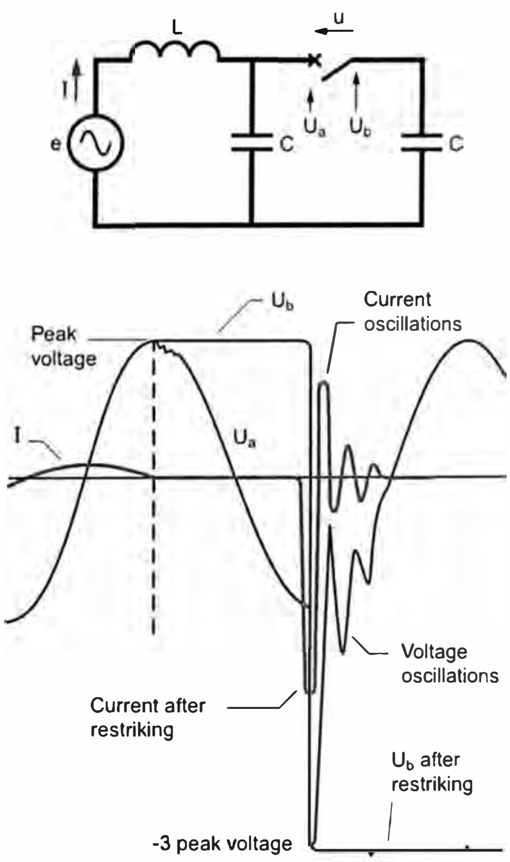


Fig. 12 : diagram of a circuit with a capacitive load: during breaking if the circuit breaker does not open quickly enough, successive re-striking can cause dangerous overvoltages for the load.

When voltage "e" is once again reversed, the peak voltage across the terminals of the switch becomes equal to 5. The overvoltage can therefore lead to re-striking again. The phenomena can continue with a voltage across the terminals of the switch capable of reaching values of 7, 9, etc.
For all re-striking occurring 1/4 of the period following zero current, an "escalation of voltage" can be observed which can lead to unacceptable peak values for loads.

On the other hand re-striking, which occurs depending on the breaking device's dimensions, is tolerable: the oscillating voltage across the terminals of the capacitor remains at an absolute value less than the peak value of the generator's voltage, which does not represent any particular danger for the devices.

As a reminder, capacitor overvoltage testing is performed at 2.25 times the rated voltage value.

Dielectric recovery of the inter-contact medium must therefore be sufficiently quick for no re-striking to occur after the quarter period.

■ Making capacitive currents and pre-striking

When closing the control device supplying capacitive loads, phenomena specific to capacitive circuits are produced.
Thus, energizing a capacitor bank causes a high overcurrent at high frequency (see **fig. 13**) for which the peak magnitude is given by the equation:

$$I_p = \frac{U\sqrt{2}}{\sqrt{3}}\sqrt{\frac{C}{L_0 + L}}$$

where
L_0 = upstream network inductance
L = capacitor bank link inductances, generally low in relation to L_0.

In the case of multi-stage banks, the phenomena is even more accentuated by the presence of the energy stored in the already energized capacitors: the transient currents can reach several hundreds of times the rated current with frequencies of several kHz due to the low values of link inductance between stages of the banks.

During pre-striking at the breaking device contacts (ignition of a conductive arc before the contacts join) these high transient currents cause early erosion of the breaking device contacts and eventually weld them. Limiting inductances (impulse impedances) are series connected with the bank in order to limit these phenomena.

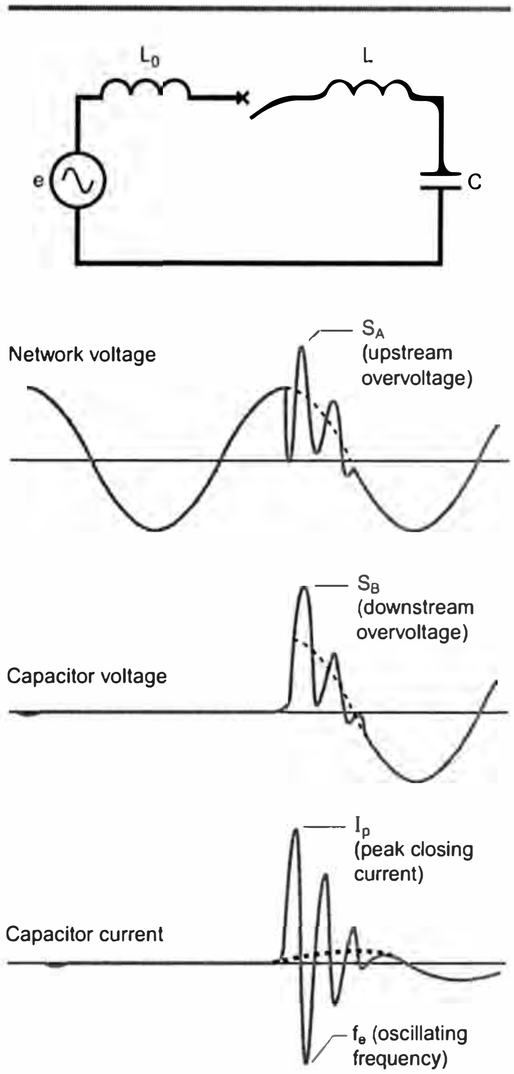


Fig. 13 : shapes of voltage and current (pre-strike overvoltage) during the coupling of a single stage capacitor to the network.

The aforementioned equation becomes:

$$I_p = \frac{U\sqrt{2}}{\sqrt{3}}\sqrt{\frac{C}{L}}\,\frac{n}{n+1}$$

where
n = number of capacitor bank stages with a value of C.
L = limiting inductances (impulse impedances), higher in relation to L_0.
Note that devices adapted to this application exist and must be specified.

■ Fields of application

Capacitive currents mainly have two origins: cables and lines, and capacitor banks.

□ Cables and lines

This involves load currents in no-load cables and long overhead lines (compensated or not). In a number of European countries (especially countries in Southern Europe, France, Italy, Spain, etc.), MV overhead networks are long and therefore particularly sensitive to atmospheric overvoltages meaning a high amount of tripping occurs on these lines... therefore a lot of re-striking.

□ Capacitor banks

Capacitor banks are series connected to the networks and are used to compensate for the lines' reactive energy (transmission network) and loads (MV/LV). They enable the transmitted active power to be increased and line losses to be reduced. They can be:

- used alone in the case of low compensation and a stable load,

- staggered (multiple or divided). This type of bank is widely used by major industries (high installed power) and by utilities companies. It is associated with an automatic control and the number of operations can be high (several operations per day): devices capable of withstanding a suitable number of operations should be specified.

■ Breaking capacitive currents and the standards

The current IEC standard 60056 (4th edition, 1987) gives values, for all voltages, of the rated breaking capacity of circuit breakers used to protect cables which may have no load. Its application is not mandatory and it is considered inappropriate for voltages less than 24 kV.

Regarding the rated breaking capacity of lines under no load, the specification is limited to devices with a rated voltage of 72 kV.

No value has been specified for capacitor banks.

IEC 60056 also specifies switching tests (see fig. 14) for protection and control devices under capacitive current conditions for lines and cables under no load and for single stage capacitor banks but does not specify anything for long lines nor for banks of filters.

Standards for capacitive current applications are tending to develop towards the definition of devices with a low probability of re-striking together with a broader specification of values and a higher number of switching operations in order to guarantee their suitability to the application.

Testing duty	Isc of the supply circuit as a function of circuit breaker's breaking capacity (Isc / Breaking capacity) x100	Testing current (% of rated I_{capa})
1	< 10	20 to 40
2	< 10	> 100
3	100	20 to 40
4	100	>100

Fig. 14 : testing specified by IEC 60056 for capacitive currents.

2.3 Breaking fault currents

In the case of a short circuit, the phase shift between the current and the voltage is always very large ($0.07 \leqslant \cos\varphi \leqslant 0.15$), since networks are basically inductive. When the current passes to 0, network voltage is at, or almost at, its maximum.

In MV, short-circuit current reaches values of a few tens of thousands of amperes. Consequently, breaking takes place without current chopping since the arc is very stable. As for load currents, arcing can be broken down into three phases:

■ a sustained arc phase till passing through zero current,

■ an extinction phase,

■ a recovery phase.

Short-circuit currents

■ The various fault types
(see Cahier Technique no. 158)

Among the various types of faults (three-phase, two phase, single phase and earthing), the most frequent fault is the single phase earthing fault (80% of short-circuits). It is generally caused by phase-earth insulation faults following over-voltages of atmospheric origin, due to broken or faulty insulation or due to civil engineering works.

Three-phase short-circuits are rare (5% of the cases) but serve as a test reference since the short-circuit current and the TRV are higher than in single phase or two phase faults.
Calculation of the fault current requires information on the network's characteristics and the neutral arrangement (insulated, directly earthed or impedant neutral). Methods of calculating have been developed and standardized (IEC 60909). Currently, calculation through computer simulation is fairly wide-spread, and all Schneider departments have developed software which they have at their disposal enabling them to obtain very reliable results.

■ Fault location

□ Faults on the circuit breaker's downstream terminals

It is under these conditions that short-circuit current is greatest since it is only limited by the impedances situated upstream of the device. Even though this type of fault is quite rare, it is the one that is chosen for MV circuit breaker specifications.

□ Line faults

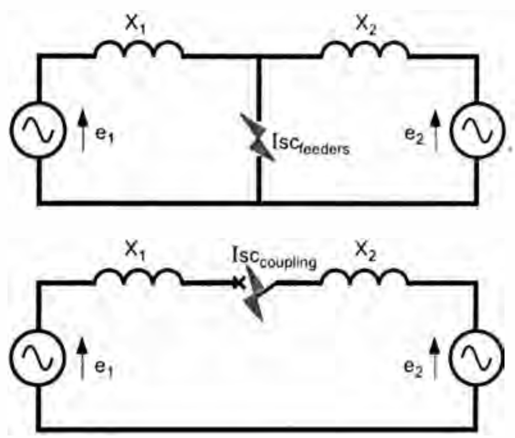
This type of fault is more common than the previous type in overhead networks, but in MV, circuit breaker arcing characteristics and circuit breaker/ cable / line connections mean that the stresses generated are less than those caused by a short-circuit across the terminals. There are therefore no specific tests for MV circuit breakers. In HV, this type of short-circuit requires specific tests for near-by faults since wave reflection phenomena cause extremely damaging TRVs.

□ Phase opposition type coupling (see fig. 15)

This is a special short-circuit scenario occurring when two unsynchronized generators are coupled.
When the two generators are out of synchronization, the voltage across the terminals of the coupling circuit breaker is equal to the sum of the voltages of each generator. The current which the circuit breaker must break can reach half the value of the current corresponding to a short-circuit at the point of coupling. The maximum is then attained during phase opposition type coupling.
IEC standard 60056 (§4.106) in this case requires that the device must be capable of breaking 25% of the fault current across the terminals at a voltage of 2.5 times the voltage to earth, covering the values encountered in practice.

■ Shape of the short-circuit current plot

The intensity of the current corresponding to the transient period during a short-circuit is the sum of two components, one symmetric or periodical (i_a) and the other asymmetric or continuous (i_c) (see fig. 16).



with $e_1 = e_2 = e$ and $X_1 = X_2 = X$

$$Isc_{feeder} = \frac{e}{X} + \frac{e}{X} = \frac{2e}{X}$$

$$Isc_{coupling} = \frac{2e}{2X} = \frac{e}{X}$$

Fig. 15 : breaking under out-of-phase conditions during the coupling of two generators which are out of synchronization.

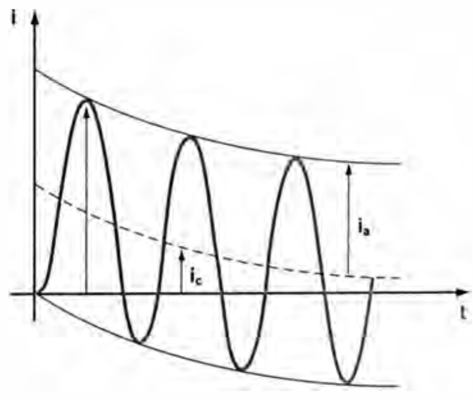


Fig. 16 : during a short-circuit the current is the sum of the two components, one symmetric or periodical (i_a) and the other asymmetric or continuous (i_c).

The symmetric component (i_a) is created by the alternating source which supplies the short-circuit current.
The continuous component (i_c) is created by the electromagnetic energy stored in the inductance at the time of the short-circuit. Its value at the moment of the fault is opposite and equal to that of the symmetric component to ensure the continuity of current. It decreases with a time constant L/R, characteristic of the network, for which the standardized value is 45 ms, resulting in the following equation:

$i_a = I \sin(\omega t + \theta)$

$i_c = - I \sin\theta \, e(-t/(L/R))$

I = maximum intensity = E/Zcc

θ = electrical angle which characterizes the time between the initial moment of the fault and the beginning of the current wave.

Two extreme cases:

□ The short-circuit occurs at the moment at which voltage (e) passes to 0. The symmetric component and the continuous component are at their maximum value. This state is called fully asymmetrical.

□ The initial moment of the short-circuit coincides with the 0 point of the current's alternating component: the continuous component is zero and this state is called symmetrical.

Breaking capacity

Short-circuit breaking capacity is defined as the highest current that a device can break under its rated voltage in a circuit in which the TRV meets a specific specification.

The device must be capable of breaking all short-circuit currents with a periodic component less than its breaking capacity and a certain percentage of the aperiodic components that do not exceed the defined value.
According to the type of device, some fault currents less than the breaking capacity can prove difficult to break. They cause long arcing times with risks of non-breaking.

■ Three phase breaking

Due to the phase shift of three phase currents, breaking occurs in the following manner:

□ The circuit breaker breaks the current in the first phase (phase 1 in figure 17) in which the current passes to zero.
The arrangement becomes two-phased and everything occurs as if point N is shifted to N'.
The voltage established in the first phase, across the terminals of the open AA' contact, is that already existing between A and N', it therefore equals:

$U_{AA'} = kV = kU_r / \sqrt{3}$

k is the factor of the first pole. Its value varies from 1 to 1.5 depending on whether the neutral is directly earthed or perfectly insulated.

□ 1/2 a period later each of the other two phases pass to zero, the circuit breaker breaks and the network becomes stable again in relation to the neutral point.
The TRV therefore depends on the neutral arrangement. The standard specifies the chosen values for the tests taking a value of 1.5 for MV in insulated neutral type networks and a value of 1.3 for other cases.

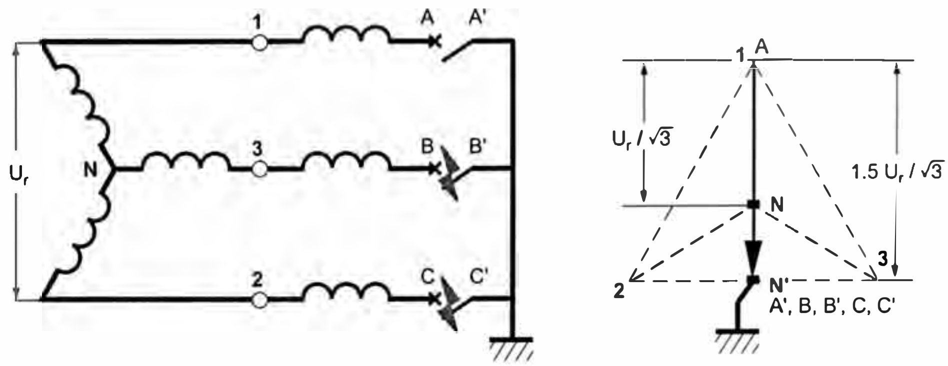


Fig. 17 : voltage $U_{AA'}$ withstood by the first pole which opens in a three phase device.

■ Closing of a circuit breaker under a fault current

Since faults are often spurious, it is common practice under normal operation to reclose the circuit breaker after interrupting a fault current. However some faults are permanent and the circuit breaker must be able to restore the short-circuit current.

Closure accompanied by pre-striking causes a high gradient voltage wave in which the current's peak can reach 2.5 Isc, supposing complete asymmetry, a time constant of 45 ms at 50 Hz and no phase shift between the poles. A closing capacity is therefore required for circuit breakers.

■ Standardized breaking capacity

Circuit breaker compliance with standards notably shows their ability to break all currents up to the rated breaking current, including the so-called critical currents.
IEC Standard 60056 (4.104) requires a series of tests enabling the validation of the device's breaking capacity and the verification of its capability in terms of repeated opening and closing switching operations.

The rated breaking capacity is characterized by two values.

□ The rms. value of the periodic component, generally called breaking capacity
The standardized values of the rated breaking capacity are taken from the Renard series (6.3, 8, 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80, 100 kA), knowing that in practice short-circuit currents have values between 12.5 kA and 50 kA in MV.

□ The asymmetric component percentage
This corresponds to the value attained at the end of a period τ equal to the minimal duration of circuit breaker opening, to which is added a half-period of the rated frequency for devices with auxiliary sources. The time constant for standardized exponential decay is 45 ms.
Other greater values are currently under research in certain particular cases.
Short-circuit breaking tests are carried out at defined TRV values, for current values of 10, 30, 60 and 100% breaking capacity according to the table in **figure 18**

The rated switching operation sequence is defined as follows, apart from in special circumstances:

□ for devices without quick automatic reclosing:
O - 3 mn - CO - 3 mn - CO
or
CO - 15 s - CO,

□ for devices intended for quick automatic reclosing:
O – 0.3 s - CO - 3 mn - CO.

with:
O = opening operation,
CO = closing operation immediately followed by an opening operation.

Testing duty	% de I_a (symmetric component)	% de I_c (asymmetric component)
1	10	< 20
2	30	< 20
3	60	< 20
4	100	< 20
5*	100	according to the standardized decay curve

*: for circuit breakers with a time τ less than 80 ms.

Fig. 18 : defined values of TRV for short circuit breaking testing of circuit breakers.

3 Breaking techniques

In order to break load or fault currents, manufacturers have developed and perfected breaking devices, and in particular circuit breakers and contactors, using various breaking mediums: air, oil, vacuum and SF_6. While breaking in air or oil is tending to disappear, the same cannot be said for breaking under vacuum or in SF_6, the "champion" of medium voltage.

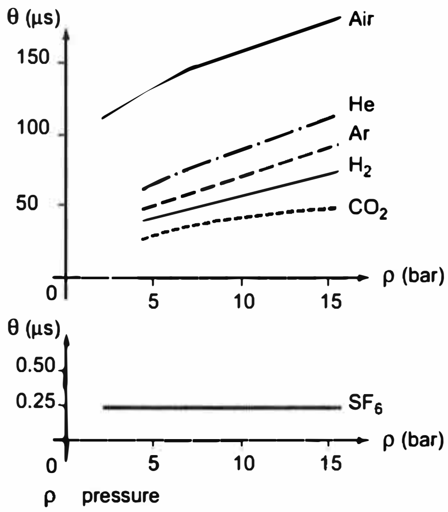
3.1 Breaking medium

The preceding chapter described how successful breaking occurs when:

- the power dissipated in arcing through the Joule effect remains less than cooling capacity of the device,
- the de-ionization rate of the medium is high,
- and the inter-contact space has sufficient dielectric strength.

The choice of breaking medium is therefore an important consideration in designing a device. In fact this medium must:

- have high thermal conductivity, and especially in the extinction phase to remove the arc's thermal energy,
- recover its dielectric properties as soon as possible in order to avoid spurious re-striking (figure 19 shows the special properties of SF_6 in this regard),
- at high temperatures, it must be a good electrical conductor to reduce arc resistance thus the energy to be dissipated,
- at low temperatures, it must be a good electrical insulator to make it easier to restore the voltage.



ρ pressure
θ deionization time constant

Fig. 19 : deionization time constants as a function of the pressure of various gases.

This insulating quality is measured by the dielectric strength between the contacts which depends on the gas pressure and the distance between the electrodes. The Paschen curve (see fig. 20 and 21), which gives the breakdown voltage as a function of the inter-electrode distance and the pressure, enables three zones to be determined according to gas pressure.

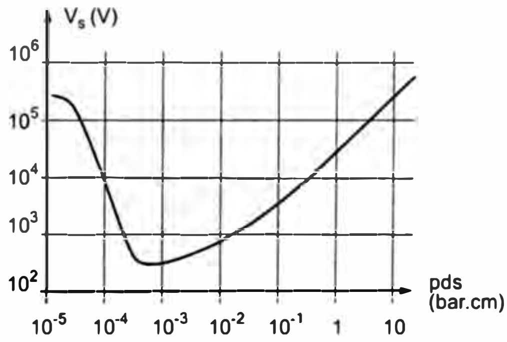


Fig. 20 : change in the dielectric strength of air as a function of the pressure, in a slightly heterogeneous field (Paschen curves).

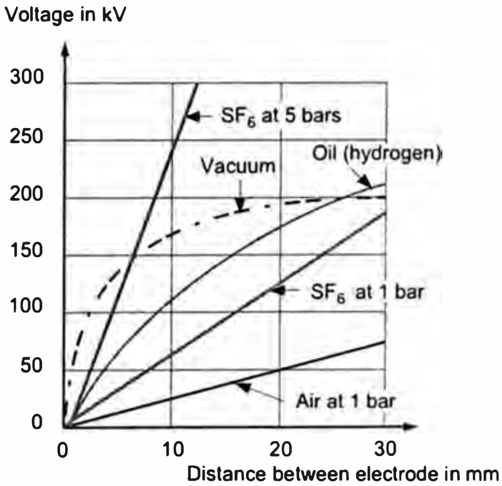


Fig. 21 : influence of inter-electrode gap on dielectric strength.

1- The high pressure zone called the "atmospheric state" in which the dielectric strength is proportional to the gas pressure and the inter-contact distance.

2- The low pressure zone in which dielectric strength reaches a true minimum between 200 and 600 V depending on the gas used (Paschen minimum). It is reached at a determined value of the product of the pressure and the inter-contact distance at around 10^2 mbar.cm.

3- The vacuum zone in which breakdown voltage only depends on the inter-contact gap and contact surface condition. Conductivity is provided by the electrons and the atoms pulled off of the contacts under vacuum and in a gas by the quick ionization of the gas' molecules.

These curves highlight the performances that are possible as a function of the breaking medium: air at atmospheric pressure or high pressure, hydrogen produced by the decomposition of oil, vacuum or SF_6. **Figure 22** shows the voltage ranges in which each of these techniques is currently used.

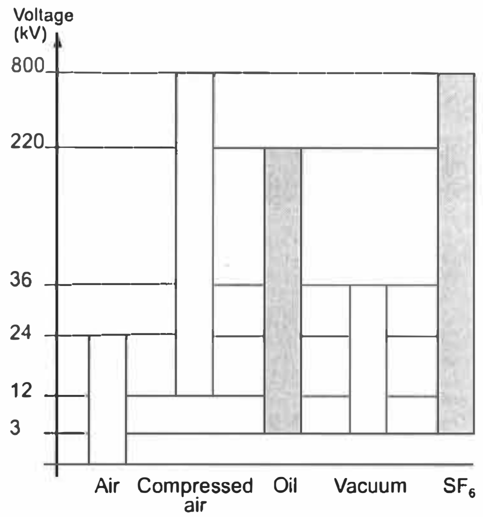


Fig. 22 : types of breaking devices used according to voltage values.

3.2 Breaking in air

Devices breaking in air at atmospheric pressure were the first to be used (magnetic circuit breakers).
Despite its relatively weak dielectric strength and its high de-ionization time constant (10 ms), air at atmospheric pressure can be used to break voltages up to around 20 kV.
For this it is necessary to have sufficient cooling capacity and a high arcing voltage after the current passes to zero in order to avoid thermal runaway.

The air breaking mechanism

The principle involves maintaining a short arc as long as the intensity is high in order to limit the dissipated energy, then lengthening it just as the current nears zero.
This principle has led to the creation of a breaking chamber for each pole of the device. The breaking chamber, situated around the inter-contact space is made up of a volume divided by refractory panels (panels with a high specific heat capacity) (see **fig. 23**) which the arc stretches between.

In practice, when the current decreases, the arc, which is subjected to electromagnetic forces, penetrates between these panels. It lengthens and cools on contact with the refractory material until its arcing voltage becomes greater than that of the network. The arcing resistance therefore greatly increases. The energy which is provided by the network then remains less than the cooling capacity and breaking takes place.

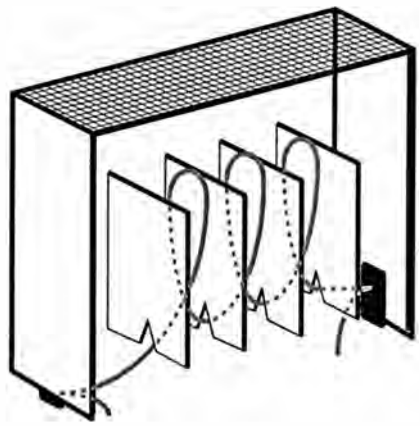


Fig. 23 : lengthening of an electrical arc between ceramic refractory panels in a breaking chamber of an air breaking circuit breaker (Solénarc type Circuit Breaker - Merlin Gerin Brand).

Due to the high deionization time constant for this technology, the arcing energy to be dissipated remains high. However, the risk of overvoltage at breaking is virtually non-existent (see **fig. 24**).

Main characteristics of an air breaking device

The dimensions of the breaking chamber are mainly defined by the network short-circuit power (in MVA).

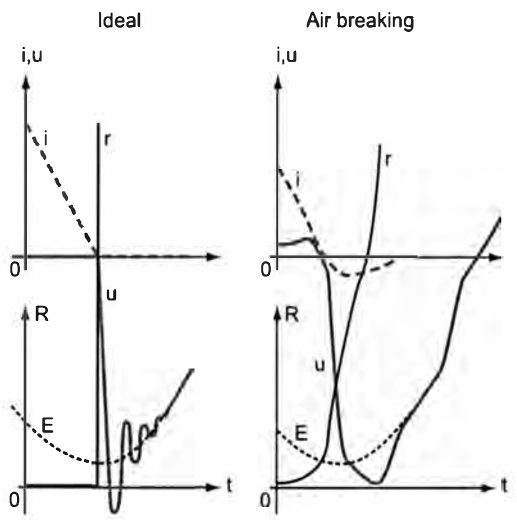


Fig. 24 : behavior comparison between an ideal device and an air breaking device.

In Solenarc type devices, the extreme length of the arc (several meters at 24 kV) is achieved in a reasonable volume thanks to the development of the arc in the form of a solenoid. Taking into account the required rate of opening of the contacts, (i.e. a few m/s), the operating energy is of the order of a few hundreds of Joules.

Fields of application for breaking in air

This type of device was commonly used in all applications but it remains limited to use with voltages of less than 24 kV. For higher voltages, compressed air is used to improve dielectric strength, cooling and deionization rate. The arc is therefore cooled by high pressure puffer systems (between 20 and 40 bars). This technique has been used for high performance circuit breakers or for higher voltages (up to 800 kV).

The air breaking technique at atmospheric pressure is universally used in LV due to its simplicity, its endurance, its absence of overvoltage and the limiting effect obtained by the lengthening of the relatively high voltage arc.

In MV other techniques have taken its place since breaking in air has several disadvantages:

- size of device (greater dimensions due to length of arc),
- breaking capacity influenced by the presence of metal partitions of the cubicle containing the device and air humidity,
- cost and noise.

MV circuit breakers using air breaking are practically no longer manufactured today.

3.3 Breaking in oil

Oil, which was already used as an insulator, has been used since the beginning of the century as a breaking medium because it enables relatively simple and economic devices to be designed. Oil circuit breakers are mainly used for voltages from 5 to 150 kV.

The principle

The hydrogen obtained by the cracking of the oil molecules serves as the extinction medium. It is a good extinguishing agent due to its thermal properties and its deionization time constant which is better than air, especially at high pressures.

The contacts are immersed in a dielectric oil. On separation, the arc causes the oil to break down releasing hydrogen (≈70%), ethylene (≈20%) methane (≈10%) and free carbon. An arcing energy of 100 kJ produces approximately 10 liters of gas. This gas forms a bubble which, because of the inertia of the oil's mass, is subjected during breaking to a dynamic pressure which can reach 50 to 100 bars. When the current passes to 0, the gas expands and blows on the arc which is extinguished.

The various types of oil breaking technologies

- High volume oil circuit breakers

In the first devices using oil, the arc developed freely between the contacts creating unconfined gas bubbles. In order to avoid re-striking between phases or the terminals and earth, these bubbles must not in any case reach the tank or join together (see **fig. 25**). These devices can consequently be extremely large.

In addition to their cumbersome size, these devices have numerous disadvantages such as the lack of safety due to the hydrogen produced which accumulates under the lid and the high level of maintenance necessary to monitor the purity of the oil and maintain its dielectric properties.

To eliminate these disadvantages (hazards, large devices), manufacturers have developed low oil volume circuit breakers.

■ Low oil volume circuit breakers

The arc and the bubble are confined in an insulating breaking chamber. The gas pressure increases as the arc passes through a successive set of chambers, then it expands through a duct in the arcing zone when the current passes to 0. The latter is therefore energetically swept, thus restoring the inter-contact dielectric properties.

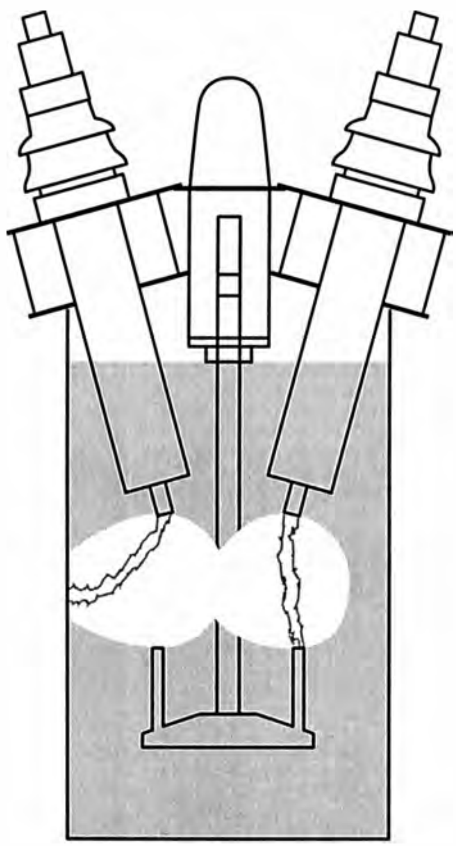


Fig. 25 : cross sectional diagram of high oil volume circuit breakers.

□ Impact of the current value on breaking capacity

For large currents, the quantity of hydrogen produced and the corresponding pressure increases are very high. In consequence the minimum arcing times are short.

On the other hand, for small currents the pressure increases are slight and the arcing time is long. This arcing time increases up to a critical level where it becomes difficult to accomplish breaking. Complementary puffer mechanisms at the end of the sequence can improve this point.

□ Main characteristics of low oil volume circuit breakers

Short-circuit current or rated current values require the mobile contact to have a minimal diameter. The length of the breaking chamber and the travel of the mobile components are practically proportional to the applied voltage. To avoid excessive pressure, the minimum arcing time to break a high current must be less than 10 ms and it must remain less than 40 ms for critical currents.

The insulating enclosure of the breaking chamber must also be designed to withstand the much higher pressure caused by consecutive faults, since the reduction of pressure requires approximately one second.

However, despite the reduction in the volume of oil, this technique still has certain drawbacks:

- Oil breakdown is not reversible.
- Oil breakdown and contact wear deteriorate dielectric strength thus causing supplementary maintenance costs.
- In the case of quick reclosing the pole remains at a high pressure and its breaking capacity is reduced.
- The risk of explosion and fire is not completely eliminated.

Fields of application for breaking in oil

This breaking technique has been widely used in electrical energy transmission and distribution. It is progressively being replaced by vacuum and SF_6 breaking techniques which do not have any of the disadvantages detailed in the preceding paragraphs.

3.4 Breaking under vacuum

The dielectric properties of vacuum have been known for a long time and have been used e.g. in vacuum bulbs and x-ray tubes. The use of vacuum in switchgear had been considered as early as 1920, but it was never applied at an industrial level until 1960 because of technological contingencies. Since the 1970s, the vacuum technique has been increasingly used due to the advantages that it offers: reduced dimensions, improved safety and greater endurance.

Dielectric properties of vacuum

In theory the vacuum is an ideal dielectric medium: there is no substance therefore there is no electrical conduction. However, the vacuum is never perfect and in any case has a dielectric strength limit.

In spite of this, a true "vacuum" offers outstanding performance levels: at 10^{-6} bar pressure, dielectric strength in a uniform field can reach a peak value of 200 kV for an inter-electrode distance of 12 mm.

The mechanism at the origin of dielectric breaking under vacuum is linked to cold electronic emission phenomena, without any ionization snowballing effect. This is why the dielectric strength is almost independent of pressure as soon as the latter is less than 10^{-6} bar. It then depends on the nature of the materials, electrode shape (in particular the presence of poinys or asperities) and inter-electrode distance. The shape of the curve of the breakdown voltage as a function of the inter-contact distance (see fig. 21) shows why the applicational scope of vacuum technology remains limited in terms of voltage. In fact the required distances for dielectric strength increase quite quickly as soon as the voltage exceeds 30 to 50 kV which leads to prohibitive costs in relation to other technologies. In addition, more x-rays would be emitted at higher voltages.

The vacuum breaking mechanism

Breaking under vacuum is fairly unique due to the specific characteristics of the arc under vacuum.

■ Electrical arcing under vacuum

The arcing column is made up of metal vapor and electrons coming from the electrodes as opposed to the other breaking techniques previously discussed where this column is mainly made up of inter-contact gas ionized by collisions.
It can occur in two ways, diffused arcing or concentrated arcing, depending on the current intensity that is present.

□ For high current values (⩾ 10,000 A) the arc is concentrated and single, as in traditional fluids (see **fig. 26a**). Cathodic and anodic spots of several mm² are raised to extremely high temperatures. A fine layer of contact material is vaporized and the arc develops in a metal vapor atmosphere which occupies all of the space. When the current decreases, these vapors condense on the electrodes themselves or on the metal screen placed for this purpose. In this arrangement, arcing voltage can reach 200 V.

□ For current values less than a few thousand amperes, this arc becomes a diffuse shape. It is made up of several arcs separated from one another and conical in shape with the peak at the cathode (see **fig. 26b**). The cathodic roots of the arcs, called spots, have a very small surface area (10^{-5} cm²) and current density is very high there (10^5 to 10^7 A/cm²). The extremely high local temperature (3,000 K) leads to very intense combined thermo-electronic / field effect emission, though the evaporation of contact material remains limited. The current is therefore basically caused by the flux of electrons.
The positive metal ions produced at the cathode have sufficient kinetic energy (between 30 and 50 eV) that they fill all of the space up to the anode. Thus they neutralize the inter-contact space charges, resulting in a low potential gradient and low arc voltage (80 V maximum).

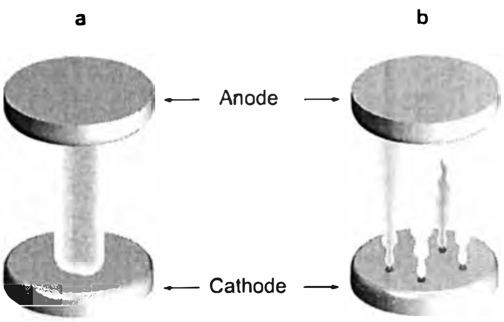


Fig. 26 : concentrated arcing [a] and diffused arcing [b].

■ Passing to 0 current

In a diffuse arcing arrangement, either obtained instantly or long enough after a single concentrated arc so that the metal vapor has had time to condense, breaking occurs easily at zero current.
In fact, when the current nears zero, the number of spots decreases until the last one which disappears when the energy provided by the arc is no longer sufficient to maintain a high enough temperature at the foot of the arc. The abrupt extinction of the last spot is the reason behind the chopping phenomena frequently encountered with this type of technology. It should be noted that at voltage reversal, the anode becomes a cathode, but since it is cold it cannot emit electrons. This thus corresponds to an excessively small deionization time constant. Vacuum devices can in consequence break currents with extremely high TRV gradients as well as high frequency currents.
For high currents, an arc plasma may remain at 0 current and breaking becomes uncertain. It is therefore essentially the density of the residual metal vapor which determines the breaking capacity.

■ Re-ignition and re-striking phenomena

These occur when the contacts release too much metal vapor. We consider that if vapor density after zero current exceeds $10^{22}/m^3$ the probability of breaking is almost non-existent.

Generally speaking, these phenomena are almost impossible to reproduce and difficult to model. Numerous tests are then required to validate the designs. In particular, dielectric failures can be observed late after breaking, eventually becoming spurious, linked to the presence of metal particles or condensation products.

The various types of vacuum breaking technology

All manufacturers have been confronted with the same requirements:

□ reducing current chopping phenomena to avoid overvoltage problems,

□ avoiding early erosion of the contacts to maintain greater endurance,

□ delaying the appearance of the concentrated arc state to increase the breaking capacity,

□ limiting the production of metal vapor to avoid re-striking,

□ maintaining the vacuum, essential to retaining breaking properties, throughout the device's life.

They have developed mainly in two ways: arc control by magnetic field and contact material composition.

■ Choice of magnetic field

Two types of magnetic fields are used: radial or axial.

□ Radial magnetic field technology (see fig. 27)

The field is created by the current circulating in the electrodes designed for this purpose. In the case of concentrated arcing, the roots of the arc move in a circular motion, the heat is uniformly distributed limiting erosion and metal vapor density. When the arc is diffused, the spots move freely on the surface of the cathode as if it were a solid disk.

The fairly complex dielectrode shapes used with this technology make dielectric strength between electrodes more difficult.

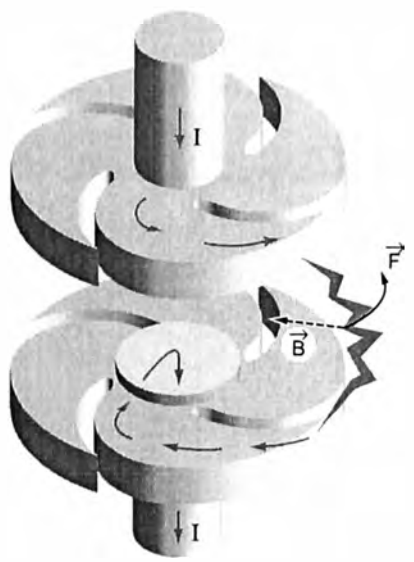


Fig. 27 : contacts creating a radial magnetic field. The arc obeys electromagnetic laws, therefore it moves from the center to the outside of the "petals".

□ Axial magnetic field technology (see fig. 28)

The application of an axial magnetic field requires the ions to take a circular trajectory which stabilizes the diffuse arc and delays the appearance of the concentrated state. The appearance of the cathodic spot is avoided, erosion is limited and this enables fairly high breaking capacities to be reached.

This magnetic field can be generated by internal or external bulb windings in which the current flows permanently. Internally they must be protected from the arc.

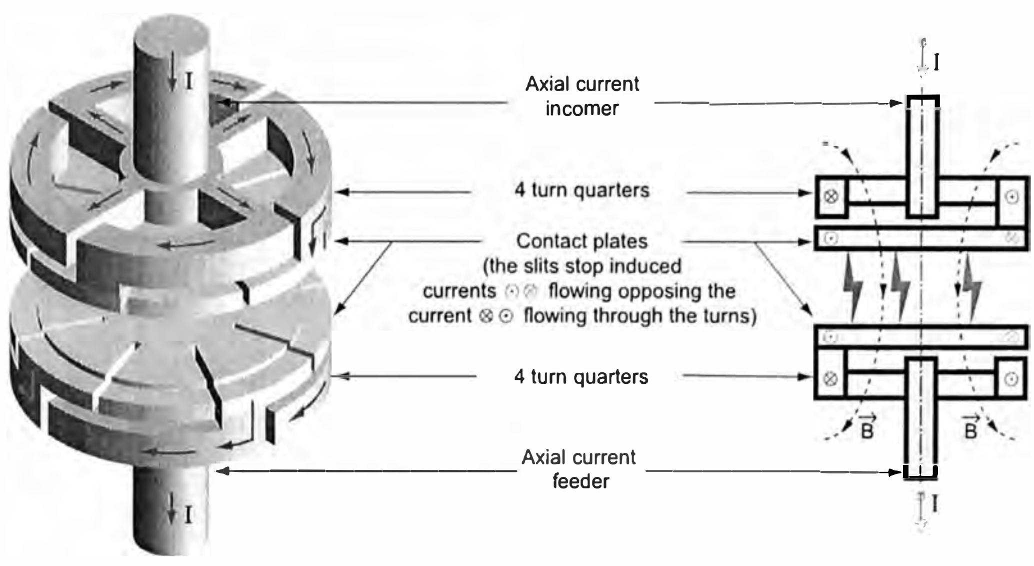


Fig. 28 : contacts creating an axial magnetic field.

Externally this risk is eliminated, but in this case, dimensions are larger and limits could arise due to the risk of the turns over-heating.

The table in **figure 29** compares both of these technologies.

■ Choice of materials

In order to maintain the quality of the vacuum, it is essential that the materials used for the contacts and the surfaces in contact with the vacuum be very pure and gas-free.

The materials that the contacts are made of is equally important since the saturating vapor pressure in the bulbs must not be too high nor too low:

	Radial field	Axial field
Contact resistance/ temperature	+	–
Arcing voltage	–	+
Contact erosion	–	+
Breaking capacity/ diameter	=	=

Fig. 29 : table comparing radial field and axial field technology.

□ High metal vapor pressure enables arc stabilization and limits current chopping phenomena (overvoltages).

□ In contrast, low metal vapor pressure is more favorable to the interruption of high currents.

Furthermore it is necessary for its resistance to be low, for it to have a low tendency to weld and good mechanical strength.

Copper/chrome alloy contacts (50-80 % Cu, 50-20 % Cr) are mainly used in circuit breakers due to their corrosion resistance, their low electrical resistance and their low vapor pressure.

Other materials such as copper/bismuth (98% Copper, 2% Bismuth) or more recently Ag/W/C are used in high switching rate devices (e.g. contactors) since they do not cause chopping and have a low tendency to weld.

Concerning the other components in contact with the vacuum, ceramic materials used with the high temperature welding process are for the moment the most suitable to maintain a high vacuum level (pressure usually less than 10^{-6} mbar).

■ Chamber and breaking device design

The key constraint is that of sealing the bulb under vacuum: e.g. mobile inserting parts must be avoided.

Particle sensitivity and the possibility of cold welding means that sliding contacts are not used under vacuum. Consequently, the contacts are simply placed end to end and the operating energy for such devices is therefore low (30 to 50 J). On the other hand, contact pressure must be high in order to minimize contact resistance and avoid separation of the contacts when a short-circuit current passes. The required contact pressure leads to high mechanical stresses.

Considering the small insulation distances under vacuum and the simplicity of the mechanisms, bulbs can be very compact. Their volume is a function of the breaking capacity (bulb diameter) however it is the dielectric strength of the external enclosure which becomes important in defining the device size.

This technology is now well mastered by major manufacturers and the devices have a life-expectancy greater than 20 years. It must be noted that permanent monitoring of the vacuum in operation is not possible since it requires a suitable metering device and de-energizing of the equipment. The predictive maintenance required, for accidental leaks, in order to monitor the reliability of the MV electrical switchboards is therefore not appropriate with this technology.

Fields of application for vacuum breaking

This breaking technique currently enables devices to be produced with great electrical endurance, and greatly increased TRV gradients.

This technique is most widely used in MV: general purpose circuit breakers are now available for various applications with all of the usual breaking capacities (up to 63 kA). They are used for protection and control of:

■ overhead cables and lines,

■ transformers,

■ single bank capacitors,

■ shunt motors and inductances.

They are particularly well suited for controlling arcing furnaces (high electrical endurance) but must be used with care for controlling parallel connected multi-bank capacitors.

This technology is also used for contactors which require high endurance, but rarely for switches for economic reasons.

In low voltage the use of this technique has remained marginal for reasons of cost and the absence of limiting power. Generally speaking, in LV its use is limited to the range between 800 and 2,500 A rated current and for breaking capacities less than 75 kA.
High voltage applications (U to 52 kV) remain for the future.

Comments :

■ When breaking capacitive current, post-breaking dielectric strength under vacuum is random, and leads to a high risk of re-striking. Vacuum circuit breakers are therefore poorly suited to protection of capacitive networks with voltages greater than 12 kV or those containing capacitor banks .

■ For vacuum contact type switches: there is a risk of welding the contacts after closing under short-circuit conditions. This is the case in certain circumstances e.g. fault locating or during standards testing cycles.
In fact, welding occurs when the contacts are closed under load. When consequently opening under no load, the lack of arcing means that the roughness, that remains from the breaking of the weld, is not eliminated. This deterioration of surface condition makes pre-arcing even easier during successive closures and increases the degree of the welding, with the risk of definitive welding taking place.
The use of these switches therefore requires certain precautions.

■ For motor control: it is necessary to take special precautions due to the fact that the circuit breakers or contactors are breaking high frequency currents (re-ignition phenomena) which therefore cause overvoltages. Even though there exist specific devices, it is preferable to associate these circuit breakers with ZnO type overvoltage protection devices.

3.5 Breaking in SF_6

Sulfur hexafluoride -SF_6-, is a gas that is appreciated for its many chemical and dielectric qualities. The breaking technique using this gas was first developed in the 1970s similarly to vacuum-type breaking.

Properties of SF_6

■ Chemical properties

In its pure state SF_6 is a non-polluting colorless, odorless, uninflammable and non-toxic gas. It is insoluble in water.

It is chemically inert: all chemical bonds on the molecule are saturated and it has a high dissociation energy (+1,096 kJ/mol) as well as a high evacuation capacity for the heat produced by arcing (high enthalpy).

During the arcing phase, in which the temperature can reach between 15,000 K and 20,000 K the SF_6 breaks down. This decomposition is virtually reversible: when the current is reduced the temperature is reduced and the ions and electrons can reform to make the SF_6 molecule.

A small number of by-products are obtained from SF_6 breakdown in the presence of impurities like sulfur dioxide or carbon tetrafluoride. These by-products remain confined in the bulb and are easily absorbed by active compounds, such as aluminium silicate, which are often placed in the breaking environment.

IEC report 61634 on the use of SF_6 in breaking switchgear gives standard values which can be encountered after several years of use. The quantities produced remain low and are not hazardous for people or the environment:
air (a few ppmv), CF_4 (40 ppmv to 600 ppmv), SOF_2 and SO_2F_2 (in negligible quantities).

■ Physical properties

□ Thermal properties

The thermal conductivity of SF_6 is equal to that of air but research on SF_6's thermal conductivity curve at high temperature reveals a peak at SF_6's dissociation temperature (see **fig. 30**).

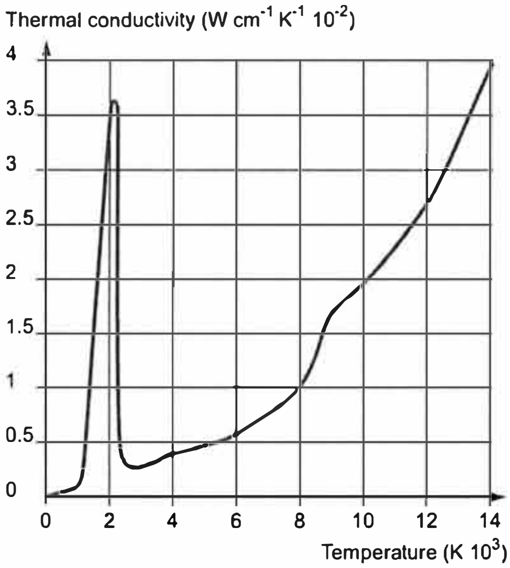


Fig. 30 : SF_6 thermal conductivity curve as a function of temperature.

□ Dielectric properties

SF_6 has a very high dielectric gradient due to the electronegative properties of fluorine (see fig. 21):
- The life span of the free electrons remains very low and with the SF_6 molecules they form heavy ions with low mobility. The probability of dielectric failure by a snowballing effect is thereby delayed.
- This gives this medium an extremely low de-ionization time constant of 0.25 ms (see fig. 19).

The SF_6 breaking mechanism

■ Electrical arcing in SF_6

Thermal study of electrical arcing has enabled it to be described as being formed by a dissociated SF_6 plasma, in a cylindrical shape, made up of a very high temperature core surrounded by a colder sheath of gas. The core and the sheath are separated by a temperature difference related to the dissociation temperature of the molecule. Around 2,000°C this threshold remains unchanged as the current intensity varies (see fig. 31).
During this arcing phase the sum total of the current is carried by the core since the threshold temperature at this stage is less than the minimum ionization temperature and the external sheath remains insulating.

The characteristic magnitudes of the arc depend on the type of breaking used (self-compression, rotary arc, self-expansion) and are given in the paragraphs discussing each of these breaking types.

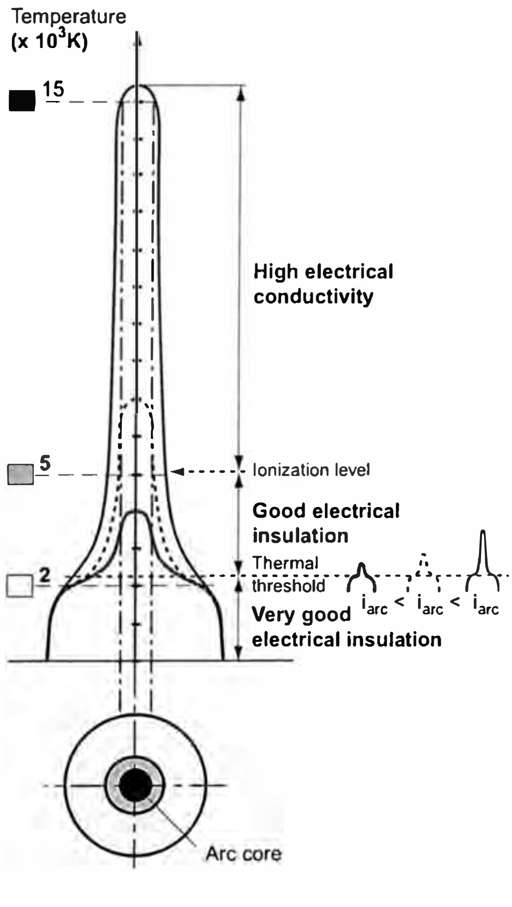


Fig. 31 : temperature distribution curve of an arc contained in a cylindrical tube filled with SF_6.

■ Passing to 0 current

With the decrease in current, the temperature of the core drops and therefore electrical conductivity also begins to fall.
Approaching zero current, the thermal exchanges between the sheath and the core become very high. The former disappears leading to the disappearance of conductivity with a time constant that is extremely low (0.25 ms) but not sufficient to break high frequency currents (no re-ignition).

Various types of SF_6 breaking technology and their fields of application

In SF_6 devices, the contacts are located within a sealed enclosure filled with gas in which the pressure varies according to voltage and design parameters. These enclosures are generally sealed for life since the leakage rate can be kept to a very low level. Pressure and / or density measurement systems can be installed which enable permanent monitoring of gas pressure in the enclosure.
Several types of SF_6 device technology exist, differing in terms of arc cooling methods and each having varying characteristics and applicational fields.

■ Self compression breaking

In this type of circuit breaker, the arc is blown out by the release of a volume of SF_6 compressed by a piston action: when the device opens, a cylinder attached to the mobile contact moves and compresses a volume of SF_6 (see fig. 32a). A puffer nozzle channels the gas in the arc axis which is then ejected in the hollow contacts.

At high currents, the arc causes a blocking effect which contributes to the accumulation of compressed gas. When the current nears zero, the arc is first of all cooled then extinguished due to the injection of new SF_6 molecules.

The average value of the arc's voltage is between 300 and 500 V.

This technology enables all currents up to the breaking capacity to be broken without any problems and without any critical current, since the energy required to blow out the arc is produced by the mechanical order which is independent of the current to be broken.

□ Characteristic values

The relative pressure of SF_6 generally used varies from 0.5 bar (16 kA, 24 kV) to 5 bars (52 kV), which enables the achievement of sealed leak-proof enclosures with guaranteed safety.

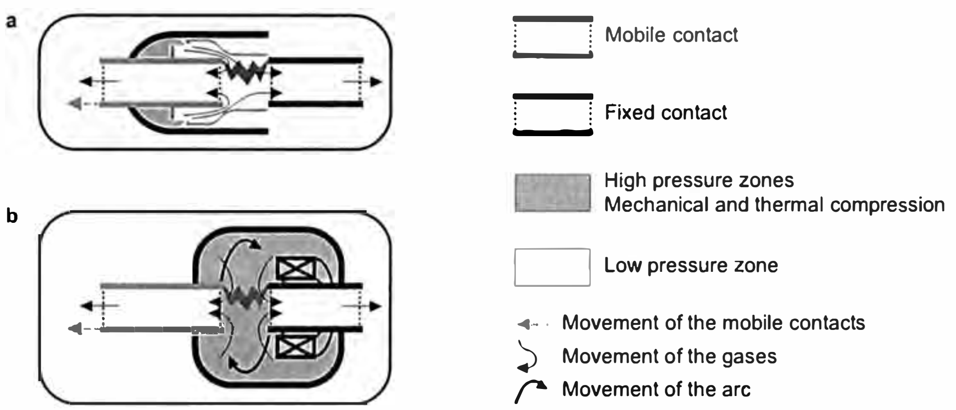


Fig. 32 : principles of self-compression [a], and rotary arc [b] breaking.

The factors influencing the dimensions of the breaking chamber are the following:

- The test voltage withstand of the input/output which determines the insulation distance between the open contacts. It can be constant and of the order of 45 mm depending on the SF_6 pressure used.
- The short-circuit current to be broken determines the diameter of the nozzle and the contacts.
- The short-circuit power to be broken determines the puffer piston dimensions (at 24 kV the volume of gas blast is of the order of 1 liter for a breaking capacity of 40 kA).

The opening energy of 200 J (16 kA) to 500 J (50 kA) remains relatively high despite the compactness of the devices due to the energy required for gas compression.

□ Fields of application for self-compression breaking

The principle of self-compression is the oldest of them all and has been used for all types of general purpose circuit breakers. It involves relatively low overvoltages since there is little chopping phenomena and there is no risk of successive re-ignition.

Self-compression circuit-breakers are well suited to capacitor bank operation since they have a low re-strike probability as well as a high endurance to closing currents.

However, the relatively high operating energy leads to quite high stresses on the operating mechanism and possibly to a limitation in terms of the number of operations.

This technology is still widely used today especially for high intensity devices and voltages greater than 24 kV.

■ Rotary arc breaking

In this technology, the arc cools through its own movement through the SF_6. The high speed rotary movement of the arc (which can exceed the speed of sound) is caused by the magnetic field created by a winding through which the fault current flows.

When the main contacts open, the current is switched to the winding and the magnetic field appears. The resulting Laplace force accelerates the arc in a circular movement. The arc contacts have the shape of circular tracks which can be either concentric (radial arc and axial field) or face to face as seen in figure 32b (axial arc and radial field). The arc is thereby cooled in a uniform manner in the SF_6. The device's cooling capacity therefore depends directly on the value of the short-circuit current which gives these devices a gentle breaking capacity only requiring low operating energy: the energy required on breaking is completely supplied by the arc and the low currents are broken without chopping or overvoltages.

Because of the quick movement of the arc's roots, hot spots releasing metal vapors are avoided and contact erosion is minimized in particular in the case of axial geometry.

It must be noted that nearing zero current, the magnetic field is reduced. It is important that it keeps a non-zero value in such a way that the arc is kept moving in the cold SF_6 when the TRV appears, thereby avoiding the appearance of critical currents This is achieved by inserting short-circuit rings which force the magnetic field to be in slight phase displacement relative to the current.

□ Characteristic values

In MV, the arc rotating in SF_6 has a voltage of between 50 and 100 V for a length of 15 to 25 mm.

Due to the low breaking energy, the devices are very compact even at a relatively low filling pressure (of around 2.5 bar) and opening energy is less than 100 J.

□ Fields of application

Rotary arc breaking is well suited to operating devices sensitive to overvoltages such as MV motors and alternators. Its excellent endurance, due to low contact wear and low control energy make it of use in applications with a high number of switching operations (contactor function).

The rotary arc technique used on its own only enables a limited breaking capacity to be achieved (25/30 kA at 17.5 kV) and only applies to voltages less than 17.5 kV.

■ Self expansion

Self-expansion breaking uses the thermal energy dissipated by the arc to increase the pressure of a small volume of SF_6 which escapes through an orifice crossed by the arc (see **fig. 33a**). As long as the current in the arc is high, it has a blocking effect which prevents the outflow of gas through the orifice. The temperature of the cold gas blocked in the volume increases due to the thermal dissipation of the arc (mainly by radiation), therefore its pressure increases as well. At zero current the plug disappears and the SF_6 expands and blows out the arc. The puffer effect depends on the current value, which enables low control energy and gentle breaking, but with a risk of critical currents as well. These are generally found at approximately 10% of the breaking capacity.

□ Two methods of arc guiding have been developed, mechanical guiding and magnetic guiding, which enable the stabilization of the arc in the puffer zone as well as the elimination of critical currents.

- Mechanical guiding (self-compression type) (see **fig. 33b**)

The arc is maintained centered between the two contacts by insulating walls confining the gaseous flux in a manner similar to the nozzles used in self-compression.

This technique is safe and simple but it increases the energy required for control. In fact, the presence of these mechanisms in the arc zone reduces the dielectric performance of the SF_6 during the restoring phase, which leads to an increase in the inter-electrode gap and contact displacement rates, and even the pressure of the SF_6.

- Magnetic guiding (rotary arc type) (see **fig. 33c**)

An appropriately dimensioned magnetic field enables the centering of the arc in the SF_6 expansion zone while giving it a rapid rotational movement similar to that with rotary arc technology. This technology, which requires expertise in design and simulation, offers the advantage of avoiding having substances other than SF_6 in the arcing zone. Thermodynamic efficiency is optimum and the SF_6 keeps all of its dielectric qualities. Therefore the insulation distances can be reduced to their minimum and the required control energy is low.

□ Characteristic values

For low currents the puffer action is almost non-existent and arc voltage generally does not exceed 200 V.

The bulb filling pressure is close to atmospheric pressure and thermal puffer volume is between 0.5 and 2 liters.

Control energy under 24 kV is less than 100 J. All of these characteristics mean that the self-breaking technique is the best performing technology to date. The breaking capacities can be very high while still having low pressure and control energy, therefore giving great reliability.

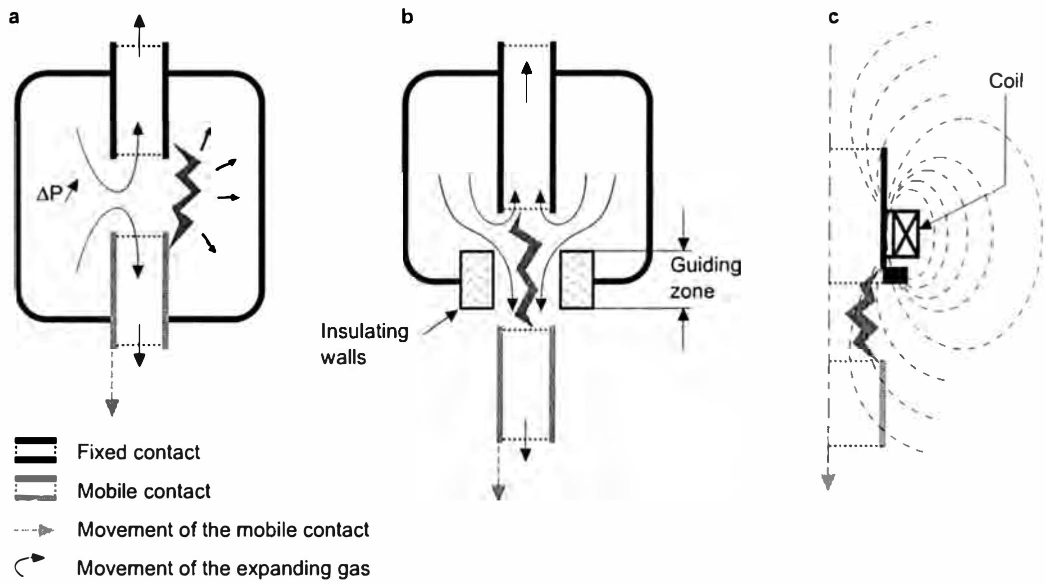


Fig. 33 : self-expansion, its principle [a] and the two methods of arc guiding, mechanical [b] and magnetic [c].

□ Fields of application

This technology, developed for breaking fault currents, is well suited for breaking capacitive currents since it accepts overcurrents and overvoltages. It is also suitable for breaking slightly inductive currents.

Without any additional means thermal expansion devices have limited breaking capacity and operating voltages. The self-expansion technique is often associated with rotary arc or piston assisted self-compression. It is then used in devices intended for MV and even in HV for all applications.

The performance levels achieved by combining thermal expansion and rotary arcing are such that the technique is considered for use in circuit breakers used in extremely demanding applications, e.g. to protect power station alternators (high asymmetry and TRV) or for applications requiring great endurance.

3.6 Comparison of the various techniques

Currently in the LV sector, magnetic breaking in air is, with the exception of a few rare cases, the only technique used.

In EHV, the SF_6 breaking technique is practically the only one used.

In MV applications, where all the technologies can be used, SF_6 breaking and vacuum breaking have replaced breaking in air for reasons of cost and space requirements (see **fig. 34**), and breaking in oil for reasons of reliability, safety and reduced maintenance (see **fig. 35**).

Vacuum or SF_6 breaking techniques have similar performance levels and their respective qualities mean that one or other is better suited for certain applications.

According to the country, one or other of these technologies is primarily used mainly for historical reasons or manufacturer's choice.

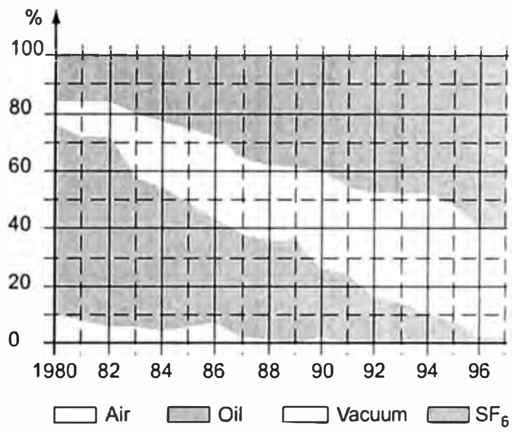


Fig. 34 : development of the MV circuit breaker market in Europe.

	Oil	Air	SF_6 / Vacuum
Safety	Risk of explosion and fire if increase in pressure (multiple operations) causes failure.	Significant external effects (hot and ionized gas emissions during breaking).	No risk of explosion nor of external effects.
Size	Fairly large device volume.	Installation requiring large distances. (unconfined breaking).	Small.
Maintenance	Regular oil replacement (irreversible oil breaking-down during each break).	Replacement of arcing contacts when possible. Regular maintenance of the control mechanism.	Nothing for the breaking components. Minimal lubrification of the control mechanisms.
Sensitivity to the environment	The breaking environment can be changed by the environment itself (humidity, dust, etc.).		Insensitive: sealed for life type bulb.
Quick cycle breaking	The long pressure reduction time requires de-rating of the breaking capacity if there is a risk of successive breaks.	The slow evacuation of hot air requires the breaking capacity to be de-rated.	Both SF_6 and the vacuum recover their dielectric properties very quickly: no need to de-rate the breaking capacity.
Endurance	Mediocre.	Average.	Excellent.

Fig. 35 : comparison of performances of various breaking techniques.

The following table figure 36 summarizes the respective features of each of these two techniques.

□ SF_6 and vacuum circuit breakers are general purpose circuit breakers and can be adapted to all applications.

Technological progress in terms of vacuum bulb production has enabled very reliable and competitive devices to be obtained in the same way as SF_6 devices.

The vacuum breaking technique is easier to implement at low voltages (voltage less than 7.2-12 kV). On the other hand, the SF_6 breaking technique enables higher breaking performances to be more easily achieved (voltage or short-circuit current).

□ Vacuum technology is widely used in control functions (contactor) (moderate voltage or current, high endurance requirement) despite the precautions to be taken concerning overvoltages.

On the other hand, it is almost non-existent in switch functions for economic reasons; in particular, the excellent dielectric strength of SF_6 after breaking enables a single device to integrate the functions of switching and isolation, which is not possible under vacuum. Today, most major manufacturers use both these breaking techniques in their switchgear according to their requirements.

		SF_6	Vacuum
Applications	Motors, fumaces, lines, etc.	All. Relatively suited to high breaking performances (I and U).	All. Relatively suited to low voltages and very quick TRVs.
	Circuit breakers, contactors, etc.	All.	Isolating functions are prohibited.
Characteristics	Endurance	Satisfactory for all current applications.	Can be very high for certain special applications.
	Overvoltage	No risk for low inductive currents. Very low probability of re-striking for capacitive currents.	Overvoltage protection device recommended for motor and capacitor bank switching.
	Isolation between contacts	Very stable, enabling isolating functions.	
	Dimension		Very compact at low voltages.
Functioning safety	Loss of tightness	Up to 80% of performances maintained at P_{atm}. Possibility of continuous monitoring.	
	Maintenance	Reduced for the control mechanism. Possibility of permanent monitoring of gas pressure.	Reduced for the control mechanism. Occasional control of the vacuum possible.
	Number of failures	Very low (< 4/10,000), mainly due to the auxiliaries.	Very low if the bulb production procedure is well controlled.

Fig. 36 : compared features of SF_6 and vacuum breaking techniques.

3.7 What possibilities for other techniques?

For several decades, engineers have been seeking to develop circuit breakers without arcs or mobile parts, notably by using electronic components.

Thyristors enable breaking devices to be produced in which the behavior can be near to the ideal switch since they break the current when it passes to zero; furthermore, their endurance is exceptional under normal conditions of operation. Unfortunately, apart from their cost, static components have a few disadvantages:

- high thermal dissipation,
- high sensitivity to overvoltages and overcurrents,
- leakage current in a blocked state,
- limitation in reverse voltage.

These features make it necessary to combine them with:

- radiators,
- overvoltage protection devices,
- ultra-quick fuses,
- switches or isolators,
- and of course electronic control systems.

Semi-conductors: thyristors, GTO, IGBT have made enormous progress and are widely used in LV in various applications, e.g. to produce contactors every time the operating rate is very high.

In HV, thyristors are placed in impedance regulation control devices comprising self-reactors and capacitors, in FACTS -Flexible Alternating Current Transmission Systems-, whose role is to optimize and stabilize the network and in Custom Power for distribution networks.

In MV, applications are very rare and static circuit breakers remain in the prototype phase; this is because, in addition to their weaknesses listed above, it is necessary to use several components in series to withstand the rated voltage.

In conclusion, except for very specific applications, static breaking currently does not have a very bright future.
Electrical arc breaking currently remains ***the*** unavoidable solution.

4 Conclusion

Of all the MV breaking techniques only SF_6 and vacuum breaking offer significantly better performance levels.

The choice between vacuum and SF_6 depends entirely on the applicational field and the technological choices made by each country and manufacturer: resulting in the differences in geographic spread of the devices using SF_6 or vacuum breaking techniques.

Currently no other technique capable of replacing vacuum or SF_6 breaking is on the horizon. These two techniques have numerous advantages relative to the older techniques:

- Safety: no risk of explosion or fire and external effects during breaking.
- Compactness: vacuum and SF_6 are very good insulators, thus the devices are not as big.
- Reliability: few moving parts and low control energy which means high availability, reduced maintenance and a very long life span.
- Placing these devices in enclosures and the production of very compact ready-made MV switchboards is another important advantage since the breaking capacity is not affected by the presence of metal partitions.

Due to current computing technology, which enables modeling and simulation, switchgear is constantly improving.
However, the most important gains in terms of operational dependability of installations (reliability, safety, maintainability) are related to the widespread use of equipment that is in a factory-made and tested enclosure, associated with the integrated protection, monitoring and control systems.

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