ABB

MEDIUM VOLTAGE PRODUCTS

Technical Application Papers No. 24

Medium voltage direct current applications

Contents

1. Introduction

Although more than a century has passed since the heated dispute between Thomas Edison and George Westinghouse known as the “War of Currents”, the debate as to whether use of direct current (DC) is better than the now widespread use of alternating current (AC) continues. Development of modern static converters, growing use of renewable energy sources (e.g. photovoltaic generation plants) and new categories of users operating directly in direct current (e.g. distribution on board ships, especially military vessels, data centers and electric vehicles) have re-opened the possibility for direct current to no longer be relegated to merely specific applications but to be used more generally, for electric power distribution.

The purpose of this guide is to provide an overview of how direct current can be applied and an indication as to the state-of-the-art and possible future developments.

2. Brief history

The modern electric power generation and distribution industry was only just dawning when, in 1882, Thomas Edison (figure 1) founded the first electricity company using direct current as its technology. The initial purpose was to supply 110 V DC for lighting people's homes using the incandescent light bulbs invented by Edison himself.

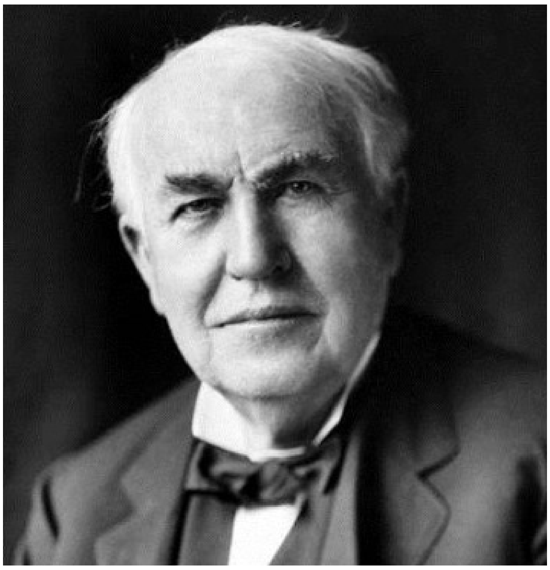

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Figure 1: Thomas Edison

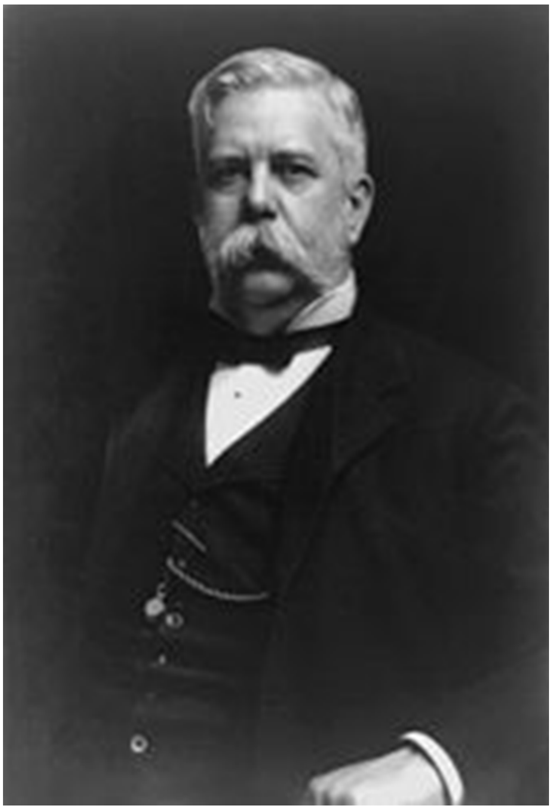

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Figure 2: George Westinghouse

The electrical supply lines were buried under the streets of New York and became rapidly popular with the public, worried about the numerous accidents due to electrocution caused by the high voltage AC lines, which had been employed since the '70's for public lighting purposes using 3500 V arc lamps.

Certain limitations to that type of use were, however, evident: the distance covered by that voltage was very limited and, to contain the costs of the copper conductors, the generating plants had to be sited within residential areas only a few kilometers from the users.
Invention, in 1884, of the high-efficiency closed-core transformer by three Hungarian inventors (Zipernowsky, Blathy, Déri) and its successive application for supplying users in parallel instead of in series, played a key role towards the supremacy of alternating current. Use of alternating current was immediately successful in Europe, and Rome was one of the first large cities to be provided with alternating current electrification in 1886.
It was during those years that, aware of what was happening in Europe, George Westinghouse, another entrepreneur and pioneer of the electricity industry (figure 2), realized how voltage step-down transformers would help towards the widespread use of alternating current while allowing him to develop new patents instead of getting round those of Edison. The first demo installation, designed to reduce voltage to 100 V AC so as to supply incandescent lamps in homes, was created in 1886 at Great Barrington, Massachusetts.
It was immediately evident to other electricity companies that, by cutting down on losses and the cost of copper lines with successive reduction for final domestic lighting purposes, high voltage transmission represented a considerable economic advantage. So much so, it quickly became widespread and the very next year, in 1887, Westinghouse and the Thomson-Houston Electric Company were already supplying more than 40% of the generating installations.

However, as use of electric power increased, the situation in certain cities as to reliability and safety became extremely critical. 6 kV AC lines with the poor quality insulation of those times were routed near all sorts of alarm lines and telegraph lines. While in the majority of European cities and some American cities, e.g. Chicago, the authorities decided to route the electricity distribution lines underground in other cities, such as New York, electricity continued to be distributed by overhead lines. The situation worsened during the Great White Hurricane of 1888 that also hit New York, causing blackouts and the deaths by electrocution of several workers as they serviced the electricity lines.

The increasing number of deaths by electrocution and the continual loss of market shares obliged Edison to take a stand and condemn AC distribution as being dangerous This was what triggered off the so-called War of Currents, which lasted for several years with no holds barred. The invention of the electric chair was even used as proof of the dangerous nature of alternating current. On the other hand, those were the years during which Nikola Telsa invented the induction motor, thereby endorsing, along with other inventions, the completeness and convenience of using alternating current.

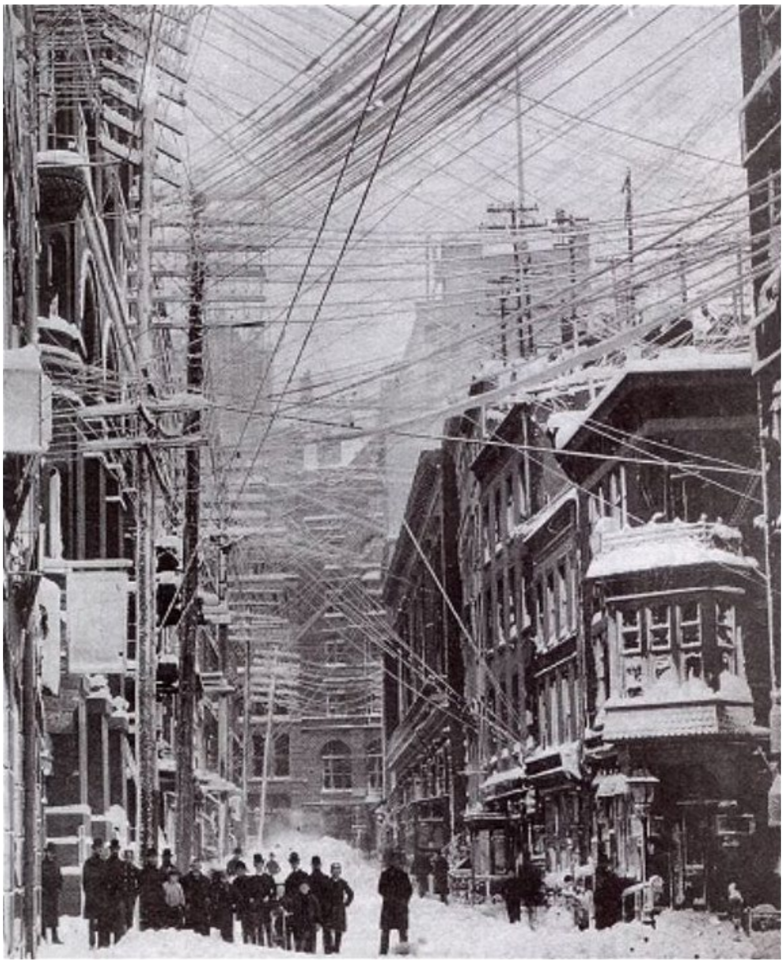

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Figure 3: New York in 1888

The corporate structures of the companies involved changed to a considerable extent in just a few years: Edison had already purchased numerous enterprises by 1890, which became a group called Edison General Electric and which, in 1892, merged with the rival company Thomson-Houston to become General Electric. Thomas Edision had by that time already lost control of the company. The two enterprises, General Electric and Westinghouse, both suppliers of AC installations, now shared the United States' electric power generation and distribution market between them.

At the International Electro-technical Exhibition held in Frankfurt, Germany, the year before, the lights and motors of the exhibition had been energized by a power station 175 km away via a three-phase transmission line by way of a demo.

The War of Currents had finally ended.

Even though certain small DC distribution networks continued to operate until the end of the '90's, AC electric power generation, transmission and distribution dominated the twentieth century and is still the most widespread system.

However, direct current is now re-awakening the interest of technicians and electricity authorities since, thanks to the developments in power electronics achieved over the last fifty years, the main problem, i.e. voltage variation difficulties, has been resolved. Modern static converters are now so reliable and efficient as to call into question the possibility of supplying direct current by harnessing its inherent advantages, first and foremost, lower transmission losses.

3. Applications and new scenarios

3.1 Evolution of electrical loads and power generation

Since AC distribution has always been predominant, designers of current-using equipment have been obliged to create such devices or their feeders for use with the AC voltage supply available. Failure to standardize the supply throughout the world, where various voltage levels are used and two or more frequencies, mainly 50 and 60 Hz, has made it even more difficult to develop products since companies have had to differentiate them to suit the market.

The recent and progressive introduction of digital devices, the internal power supply of which is necessarily in DC, has forced designers to develop conversion stages, i.e. AC/DC rectifiers, so as to connect them to the grid, initially without worrying too much about their efficiency.

Nowadays, and even though progress has been achieved as to the efficiency and control of these rectifiers, the massive presence of such loads is forcing a rethink regarding the structure of the existing power distribution grid.

Loads energized directly in AC are also rapidly decreasing in sectors such as that of electric motors, which has always been dominated by AC supply systems. Our homes and offices contain a huge number of personal computers, printers, telephones, televisions and Hi-Fi systems. All these devices are powered in DC via rectifiers and already represent about 20% of the total electric power consumption. Considering the increasing use of LED lights, much more efficient than the incandescent ones invented by Thomas Edison, electric vehicles (charged in DC with a considerable load) and all those loads traditionally powered in AC (e.g. washing machines and air conditioners) but which now use static frequency converters or inverters for improved efficiency and to control the speed of their motors, it is easy to forecast that DC loads will reach 50% of the total consumption within the next few years.

It is worthwhile remembering other DC processes used in industry, such as electric arc furnaces (available in AC and DC, but more efficient in this latter case), certain electrochemical processes, railways, telecommunication systems and data centers, auxiliary services and protection systems for power stations and primary substations, all UPS (Uninterruptible Power Supply) systems and, generally, all storage systems based on batteries.

Thus, the chance to save up to 15 - 20% of the total energy losses by supplying these loads directly in DC or improving converter efficiency by eliminating the rectifier module, is bound to increasingly encourage the use of direct current.

3.2 Power generation from renewable sources

Another important thing to consider is the rapid increase in electric power generation from renewable sources, backed by governments and public opinion worried about the rapid climatic changes (see Technical Guide: Smart grids – 1. Introduction).

The main sources of DC power supply are photovoltaic panels (PV) and, to a much lesser degree, fuel cells. At the present time, these two sources need inverters to connect to the AC grid. Electric power storage systems based on batteries also need inverters for connection, plus a complex control system for the charging and discharging phases. Wind-powered generators can produce in both DC and AC. Nowadays, generation typically occurs in AC with long 36 kV connection lines between the wind farms and distribution grid.

In view of the widespread installation of photovoltaic panels on buildings for both domestic use and in the services-providing sector, buildings could already be erected with their own DC network, thereby achieving perfect integration between generation and consumption, as will be discussed further on.

3.3 Static converters

The current AC distribution grid structure needs three types of static converter for connecting loads and distributed generation:

- AC-DC converters, also called rectifiers: these devices supply a continuous outgoing quantity from an alternating incoming quantity;
- DC-AC converters, also called inverters: devices which supply an alternating outgoing quantity from a continuous incoming quantity;
- AC-AC converters, devices with both an incoming and outgoing alternating quantity. They are normally used for starting and adjusting electric motors under the name of drivers.

Instead of the above, DC grids have DC-DC converters. These devices have both an incoming and outgoing continuous quantity for the purpose of varying the voltage level, as in the case of AC transformers.

Different types of semiconductor devices are used in static converters:

- **diodes** are devices that are only able to conduct current in one direction and cannot be controlled;
- **SCR** (Silicon Controlled Rectifier) belongs to the thyristor family used for controlling the passage of current from anode to cathode;
- **GTO** (Gate Turn-Off thyristor) is a device whose transition from the conducting state to the inhibited state is easier to control than that of the SCR;
- **TRANSISTOR BJT** (Bipolar Junction Transistor) here again, this is a device that allows the current to be controlled more easily;
- the **TRANSISTOR MOSFET** (Metal Oxide Semiconductor Field Effect Transistor) is a component that can be switched on and off by means of a voltage signal applied to a terminal. It switches very fast thanks to an extremely simple control circuit (turn-off times are around 100 ns);
- **TRANSISTOR IGBT** (Insulated Gate Bipolar Transistor). A component that combines the low conduction losses of the BJT with the switching speed of MOSFET;
- lastly, the **MCT** (MOS-CONTROLLED THYRISTOR) possesses many of the properties of the GTO, such as low dissipated power at medium current and the same switching speed as the IGBT. However, owing to its complexity, it is unable to reach the high current values reached by the GTO.

Switching times and the power involved are the main and most significant differences among the components described above. SCR and GTO are to be preferred for high powers, since they withstand higher voltages and currents than those of a transistor (3000 V/ 3500 A for a diode, 3000 V/1000 A for an SCR, 3600 V/600 A for a GTO, 400 V/250 A for a transistor).

On the other hand, the switching times of a transistor are less than 10 µs against 40 µs for an SCR and 25 µs for a GTO.

Thus transistors are better if the power involved is relatively low and since they are easier to control, they become the only choice, especially in the case of high-frequency converters.
Table 1 outlines the main characteristics described above in a qualitative manner.

	Diode	SCR	GTO	BJT	MOSFET	IGBT	MCT
Power handling capability	High	High	High	Medium	Low	Medium	Medium
Switching speed	-	Slow	Slow	Medium	Fast	Medium	Medium

Table 1: main characteristics of semiconductors for electric power conversion

The graph in figure 4 below translates these peculiar characteristics into industrial application terms:

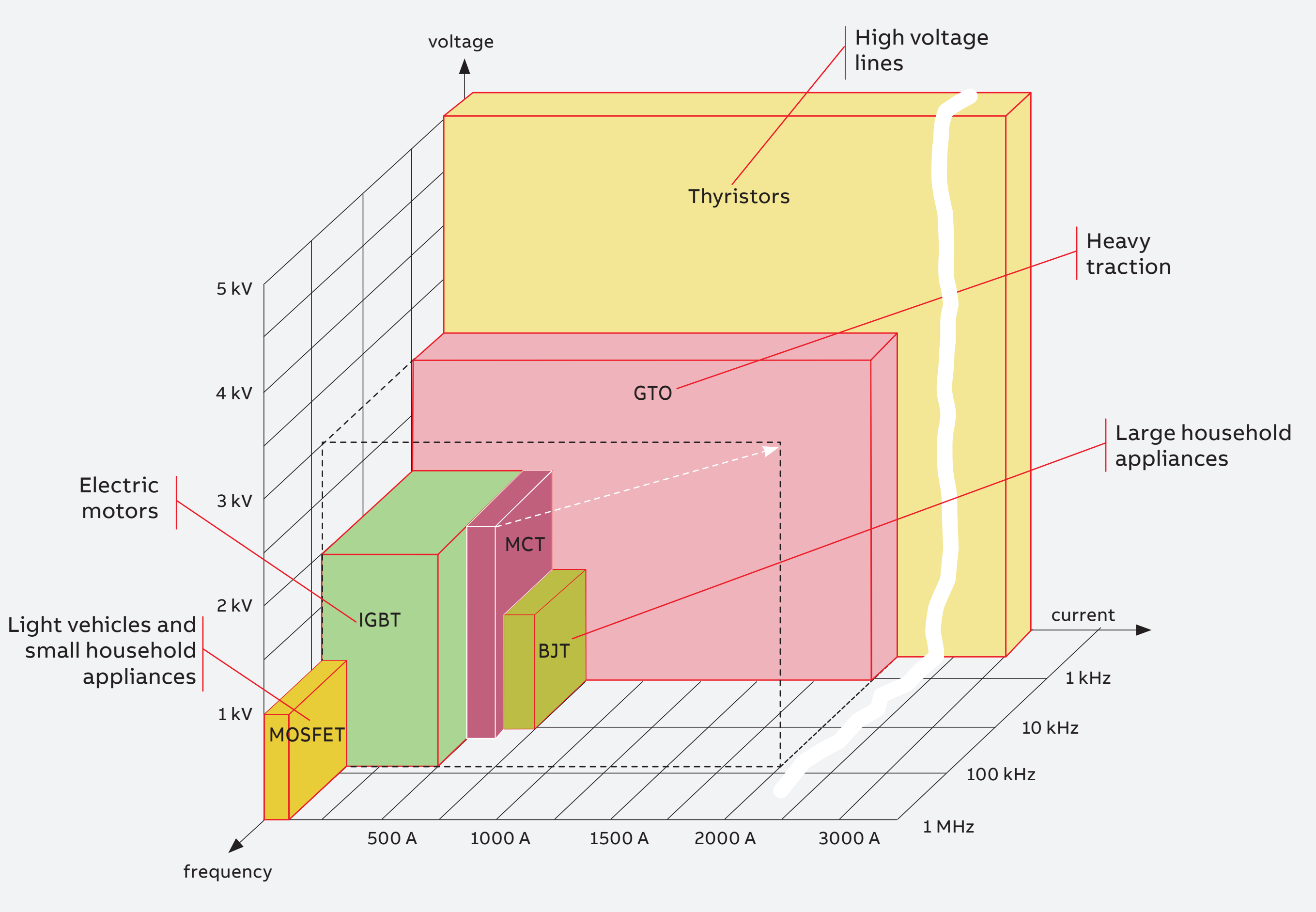

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Figure 4: limits and applications of electronic components for AC/DC conversion

Depending on the type of use required and their characteristics, some of the components described previously can be used for designing a static converter. The main criteria are:

- voltage and current of the application and consequent losses;
- switching time;
- ease with which the component can be controlled;
- temperature coefficient of the component in the case of connection in parallel to obtain higher currents;
- cost of the component.

AC-DC CONVERTERS or RECTIFIERS

An AC-DC converter converts an alternating (voltage or current) signal into a continuous signal. Rectifiers can be used for numerous purposes:

- DC drives for industrial use (e.g. rolling mills, wire drawing machines, newsprint machines, conveyor belts, positioning systems, robot drives, etc.);
- DC traction power with alternating feeder lines (trolley buses, train and subway locomotives, cable railways, cable cars, etc.);
- supply systems for certain electrochemical processes;
- terminal converter substations for HVDC transmission lines;
- the incoming DC supply stages required from DC/DC and DC/AC converters.

DC/DC CONVERTERS

In a DC-powered system, a DC-DC converter is used to vary the DC voltage supplied to the load. This variation is obtained by varying the fraction of time in which the load is connected to the power supply. These converters are used as direct current feeders in different sectors:

- electronic equipment such as computers;
- avionic and space applications;
- laboratory power suppliers;
- speed adjustment of motors in DC-powered electric traction systems and with DC propulsion (railways, subways, electric vehicles).

DC-AC CONVERTERS

These devices, also known as inverters, convert incoming direct voltage to outgoing alternating voltage, which can be adjusted both as to amplitude and frequency. These converters are used as AC feeders in different sectors:

- variable speed drives in DC systems with AC motors, where the motor must be supplied with voltage and current with variable frequency and amplitude;
- uninterruptible power supply units powered by DC via storage batteries in which the inverter draws the power required to supply the load in the absence of mains voltage;
- medium frequency furnaces for induction heating;
- insulation stages based on the use of high-frequency transformers, especially as second stage in DC/DC converters when insulation between input and output is required.

AC-AC CONVERTERS

An AC-AC converter consists of a rectifier, which may or may not be controlled, installed in series with an inverter. Using these converters, it is possible to both vary the amplitude of the output signal by adjusting the trigger times in the rectifier stage or the trigger sequence in the inverter stage, and to change the frequency of the output signal by adjusting the on and off times of the components in the inverter. Some of the uses for these types of converters are listed below:

- in the power supplies of aircraft so as to obtain the 400 Hz frequency typical of avionic applications and for regulating lighting and heating systems;
- in the drives of AC motors, especially for starting and adjusting the speeds of large three-phase motors;
- in household appliances, for governing the speed of their small motors.

AC distribution networks normally include at least three types of converters, such as rectifiers, inverters and AC/AC converters. The evolution of electrical loads and distributed generation involves the increasing use of static converters. Figure 5 below illustrates the simplified structure of a modern AC distribution grid.

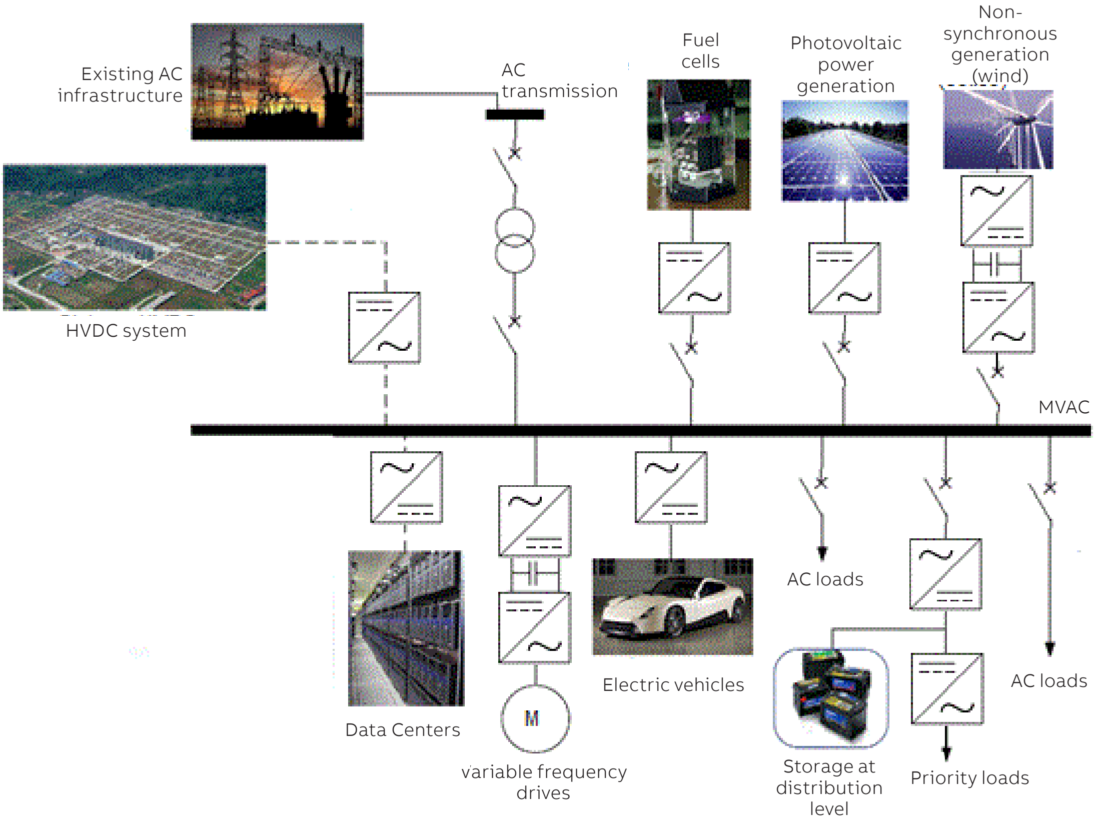

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Figure 5: structure of a modern AC distribution grid

A similar structure but with DC distribution is illustrated in the next figure 6:

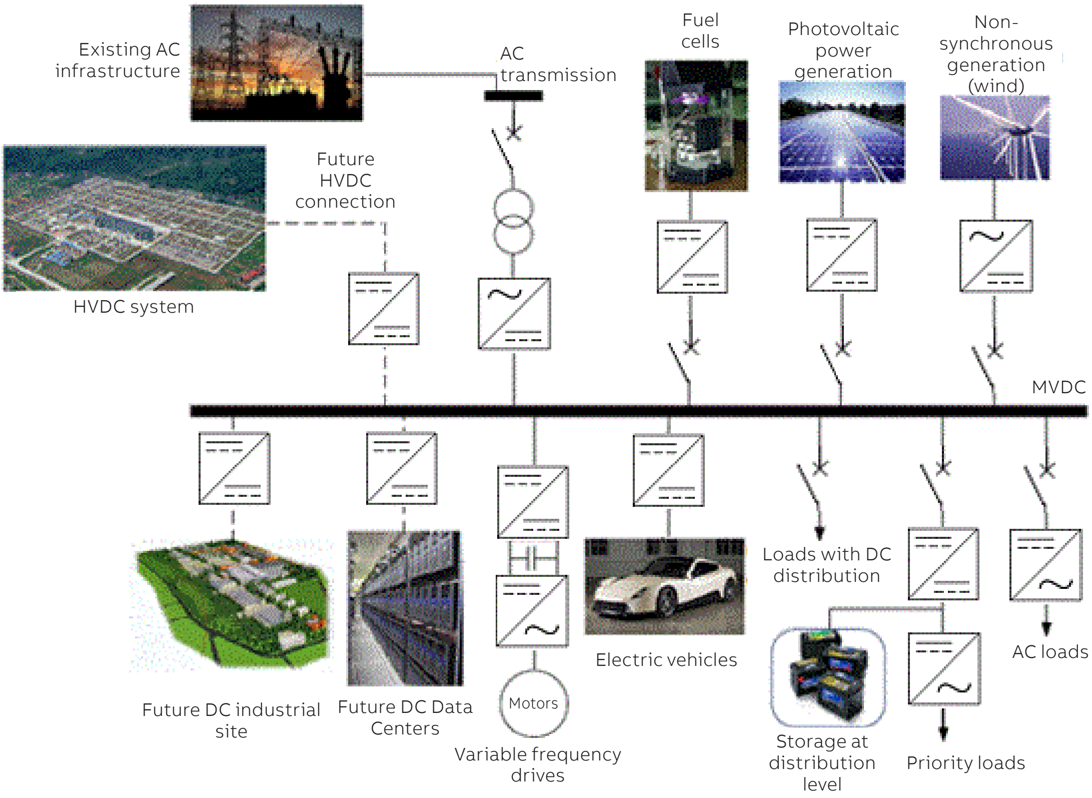

Figure 6: hypothetical DC distribution grid

As can be seen by comparing the two diagrams, the DC distribution system requires DC/DC converters, which actually replace the AC/DC rectifiers almost completely.
In addition, a process for standardizing the DC voltages on the market would reduce the need to use many of the DC/DC converters on individual loads. DC distribution would therefore be particularly convenient in limited, independent areas and with specific functions, generally in microgrids.

3.4 Protection of static converters for AC/DC interfacing

As explained in the previous section, DC microgrids normally include power generation from renewable sources (e.g. photovoltaic systems) and will also include DC storage systems and local loads to an increasing extent.
In addition, there will always be a static power converter to interface with the AC grid.
The most widely used earthing system in medium voltage AC installations is the isolated neutral type, while several solutions are available for DC installations, depending on the safety and continuity level required. Not only does the earthing system change, but also the behavior of the DC system in the case of faults. In some cases, the converters could be unable to limit the fault current and could therefore be damaged. This would require the installation of DC rapid interruption apparatus.

Now let's look at the circuit illustrated in figure 7 below:

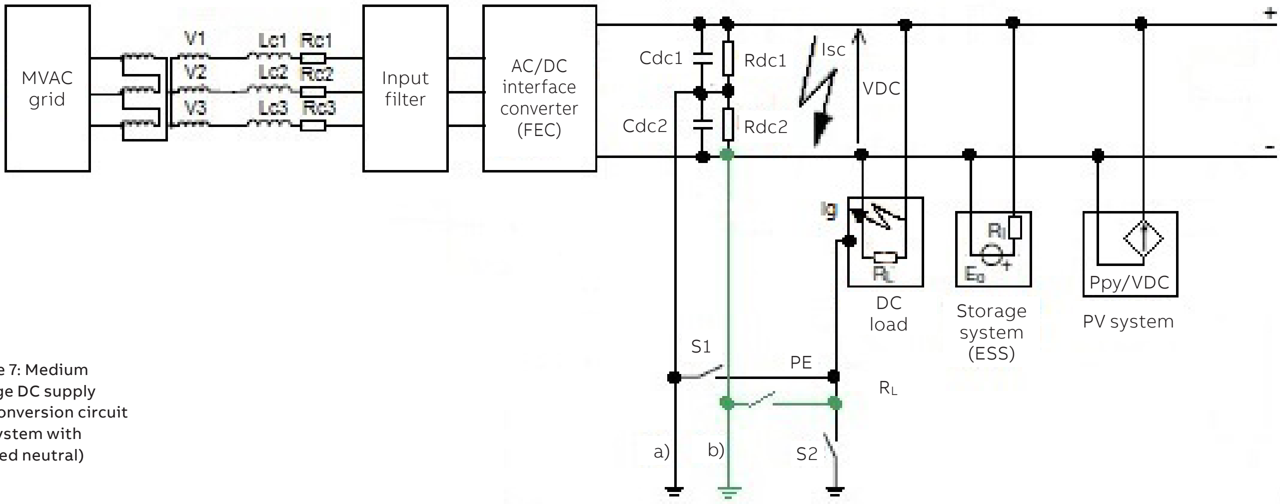

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Figure 7: Medium voltage DC supply and conversion circuit (AC system with isolated neutral)

Where the midpoint connections a) connected to earth and b) negative pole connected to earth, are alternatives. The circuit includes:

- a bidirectional AC/DC interface converter (Front-End Converter or FEC) which controls the voltage value on the DC side;
- an Energy Storage System (or ESS) to ensure a continuous supply to priority loads, normally connected by means of a bidirectional DC/DC converter;
- a photovoltaic system (PV) connected to the DC system by means of a DC/DC step-up converter;
- a generic DC load represented by a generic resistive element.

If a fault occurs between the poles immediately on the load side of the FEC, the fault current depends on the resistance of the fault itself. If this is less than the maximum threshold setting of the protection of the electronic components, the FEC self-controls so as to keep the voltage (VDC) at rated value. The value of the current supplied will be higher, but still close to the value of the rated current of the actual FEC. If current Isc exceeds the threshold value, the converter protection system will limit the current consumption of the AC network to a value that will not damage the components, thus also limiting the active power transferred to the DC network. In these conditions the voltage (VDC) decreases until reaching the value corresponding to the maximum power absorbable by the AC side. In addition, if the fault resistance is very small and the VDC drops to less than 2 √2 V1 (where V1 is the root-mean-square value of the neutral phase voltage on the AC side), the converter will begin to over-modulate. In this condition and for a fraction of time that increases as the fault resistance decreases, the current will

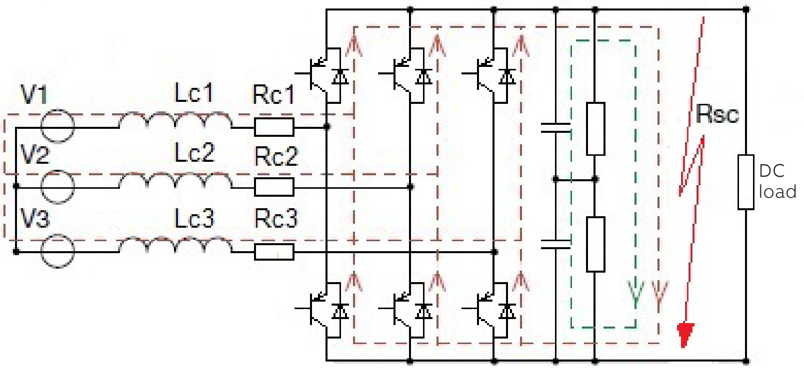

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Figure 8: currents in the converter circuit in the presence of short-circuit between poles

no longer be controlled and could exceed the value established for switching the components. This consequently creates a distortion in the current on the AC side. Lastly, when the fault resistance is near to zero, the converter acts like a rectifier with short-circuited diodes. In this case, the semiconductors controlled are excluded and the current passes through the freewheeling diodes (figure 8).

In these conditions, the only thing that can limit AC current consumption is the impedance of the MV network, with consequent damage to the semiconductors. The current is also strongly distorted by the presence of low frequency harmonics for as long as the fault lasts.
Earth faults are the next situations to be addressed. Even though the power is notmally supplied by means of the FEC, the ESS is also able to provide the system with energy and is shown in figure 7 as a voltage generator E_0. If a fault occurs in a DC system, this converter initially supplies a peak current due to the capacitors having discharged and will continue even afterwards to supply the fault by means of the freewheeling diodes without any further control by the converter.
In photovoltaic installations, the task of the converter is to maintain the operating point of the installation at its maximum power and adapt the voltage to that of the system. In this case, it is depicted as a current generator equal to P/VDC. If a fault occurs in a DC system, there will initially be a peak current after which the converter will continue to supply the fault with a short-circuit current equal to 1.25 times the maximum current in normal conditions. Here again, the converter is unable to limit the current, which flows by means of the freewheeling diodes.

The next situation considered is when the midpoint is earthed (connection "a" in figure 7). The voltage of the pole affected by the fault tends towards zero, while the voltage in the unaffected pole fluctuates and can reach the full rated voltage value. This could create insulation problems (if sized for VDC/2). If an earth fault occurs in a generic load, current Ig will flow through the midpoint (figure 9). Since direct fault current does not reclose through the converter, this latter continues to maintain constant VDC voltage on the load regardless of the fault resistance value.
Current Ig is therefore excluisvely due to capacitors Cdc having discharged. The situation does not change even in the presence of ESS and PV. Both continue to supply the load normally but not the fault, apart from the transient due to the capacitors having discharged. In the case of PV, the current is limited to the maximum value of I_{PVmax} (P_{PV}/VDC).
If, on the other hand, the negative point is earthed (connection "b" in figure 7), an earth fault in the positive pole will cause a short-circuit between the poles. This means that no direct component passes through the converter, which acts as though the fault were a low impedance load. This case is similar to the first one considered (fault between poles immediately on the load side of the FEC).
Further details are given, especially about LV grids, in “Technical Application Papers No.14 – faults in LVDC microgrids with front-end converters” and in [36].
In view of the above, it is evident that to prevent the electronic components from being damaged, the interface converter on the DC side must be protected against short-circuit between poles and against earth faults by high-speed circuit-breakers.

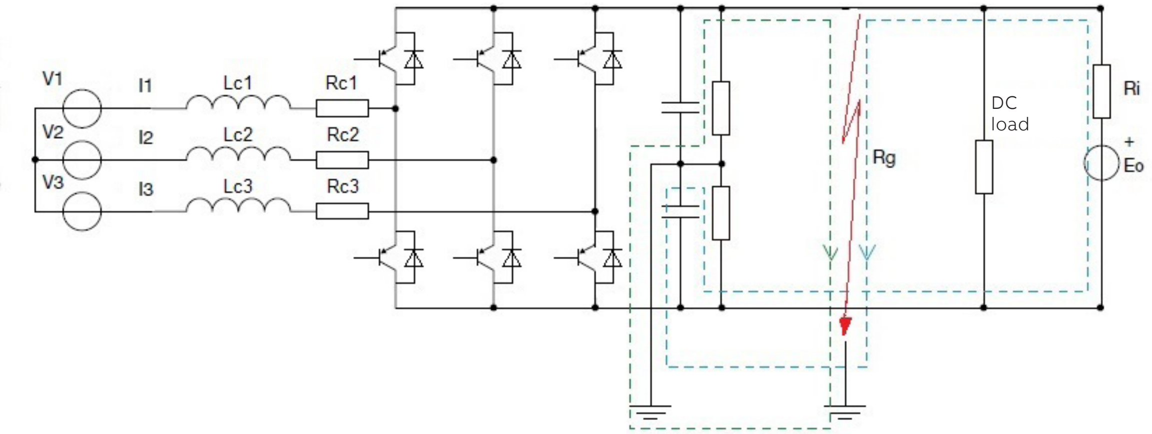

Figure 9: currents in the converter circuit in the presence of earth fault

3.5 DC microgrids

A microgrid can be considered as a group of electric power sources, loads and storage systems with well-defined limits from the electrical aspect, which functions both as an isolated entity disconnected from the network and, vice versa, connected to the network itself. Thanks to the development of new types of electrical loads and sources, this definition can cover many applications especially in future-oriented terms.

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Figure 10: Shopping Center

3.5.1 Office blocks and shopping centers

Many public and private consortia and initiatives throughout the world are now actively involved in the subject of Smart Buildings. Use of an internal DC distribution grid is one of the most interesting issues being addressed. Regarding office blocks and shopping centers, it is worthwhile mentioning the initiatives promoted by Emerge, a consortium of companies (figure 11), professionals and institutions to which ABB also belongs and which aims to standardize the DC electric power distribution system in office buildings and shopping centers. Achieve zero energy balance in the next generation of buildings is the goal.

The basic idea is to promote the use of direct current and integrate the main services inside and outside the buildings so as to achieve enhanced flexibility and reliability, consume less energy with lower investments and obtain buildings with zero energy balance where the power consumed is the same as that produced. The DC grid would distribute the power (generated by photovoltaic panels for example), store it and use it to supply indoor and outdoor LED lights, the Data Center and all the computers, communication devices, charging points for electric vehicles and the building monitoring and automation system (figure 12).

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Figure 11: the companies belonging to the Emerge consortium

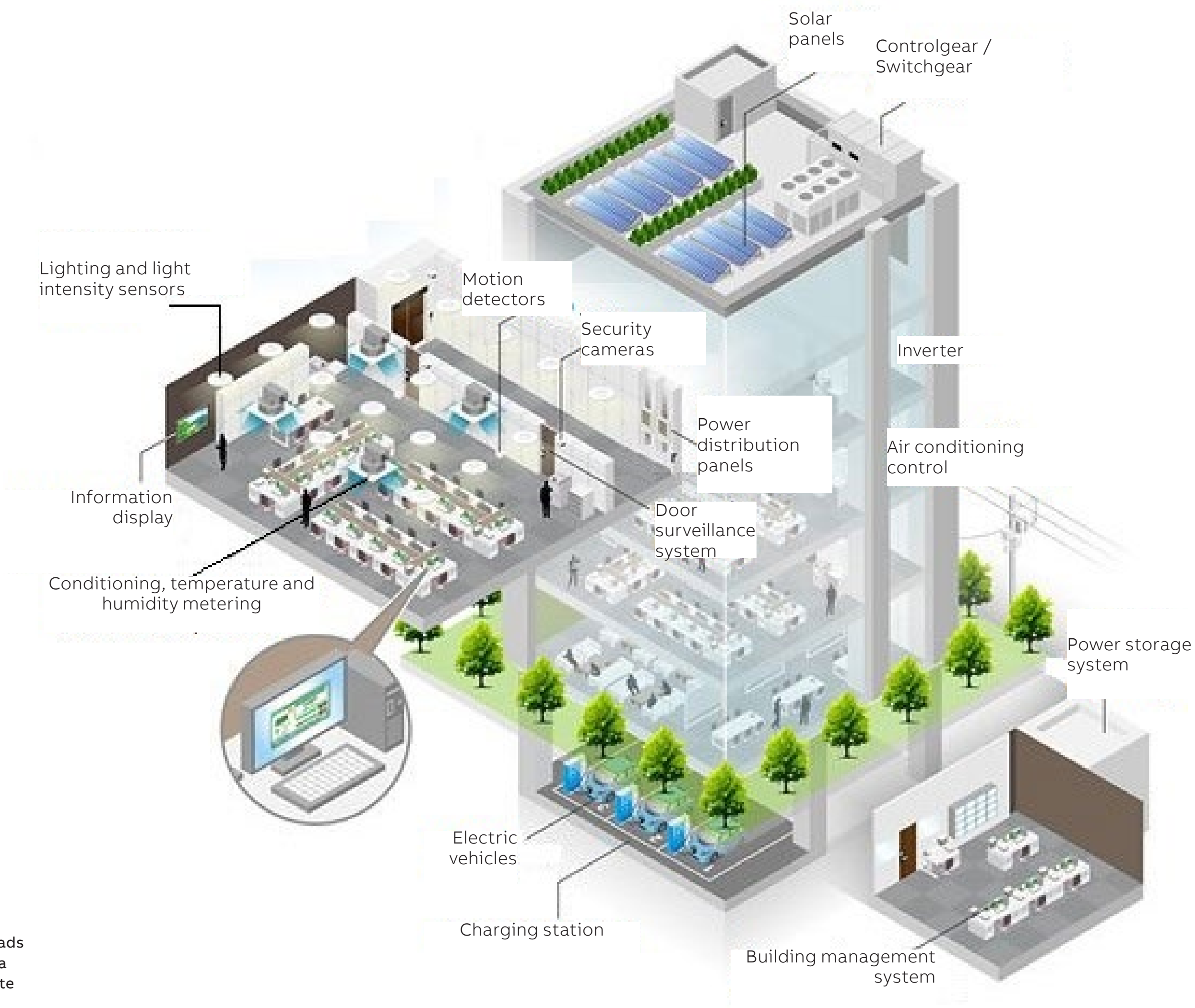

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Figure 12: DC loads and supplies in a residential estate

Thus the consortium also focuses on creating new standards, the aim being to reduce the number of conversions in the connection between sources and user devices to the minimum.

3.5.2 Rural applications

The cost of installing the infrastructures required to convey electricity to remote rural areas can be prohibitive. A microgrid could be the ideal solution in such cases, since it would allow the area in question to become independent thanks to distributed generation based on renewable sources such as photovoltaic panels or wind-powered generators. So much so, not only can this solution make the electrification of remote areas economically feasible, but also sustainable from the environmental aspect. The stability of a microgrid can be increased by means of an energy storage system based on batteries. The typical electric loads range from high-efficiency LED lighting both inside the buildings and surrounding area and along the roads, to both DC and AC electric motors and pumps, communication systems, computers and other electronic devices, which could even be directly supplied by DC.
Figure 13 gives an example of how a photovoltaic source and water pumping and distribution could be integrated for a rural application.

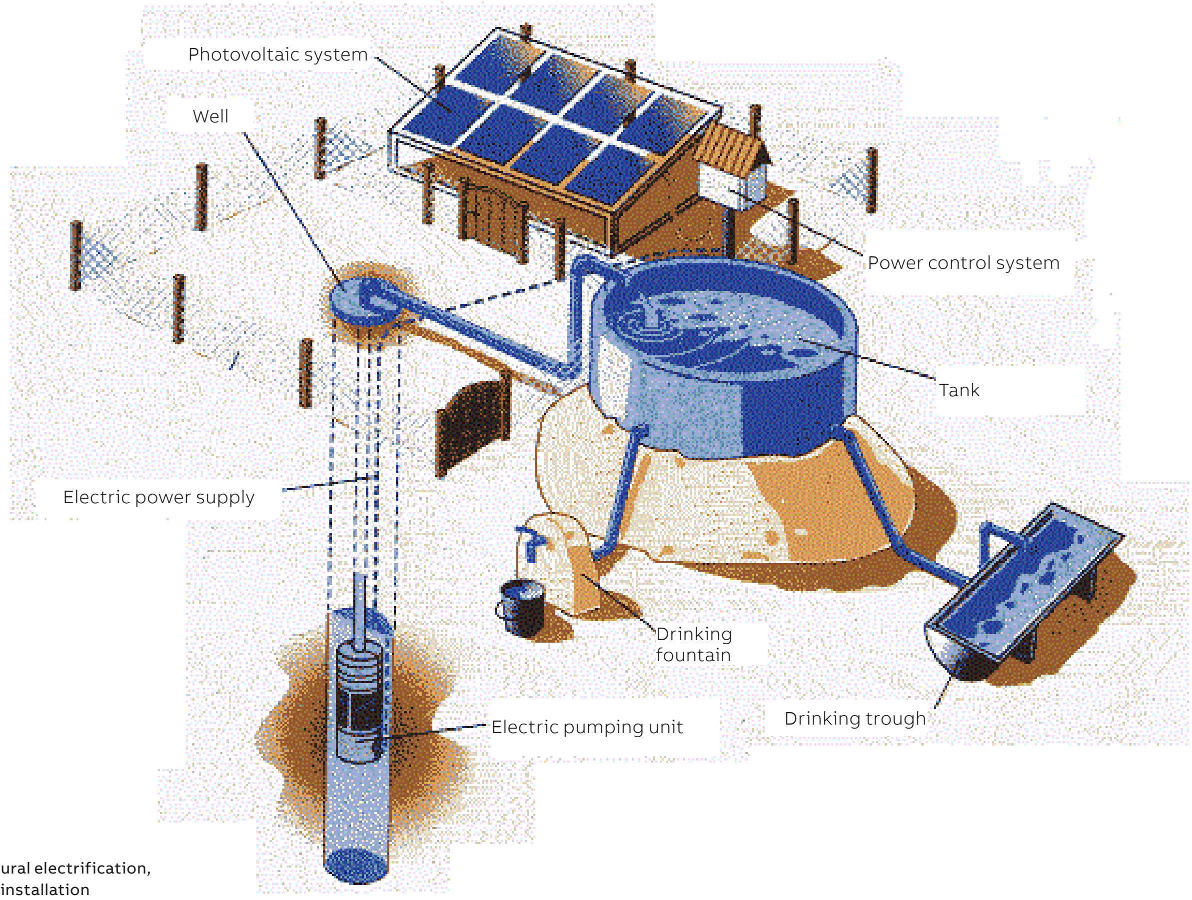

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Figure 13: Rural electrification, diagram of installation

As already explained for office blocks and shopping centers, here again DC loads will probably become predominant in the future and this would make DC electric power distribution convenient. The remaining AC loads and the energy generated by wind-power could be connected by means of inverters (figure 14).

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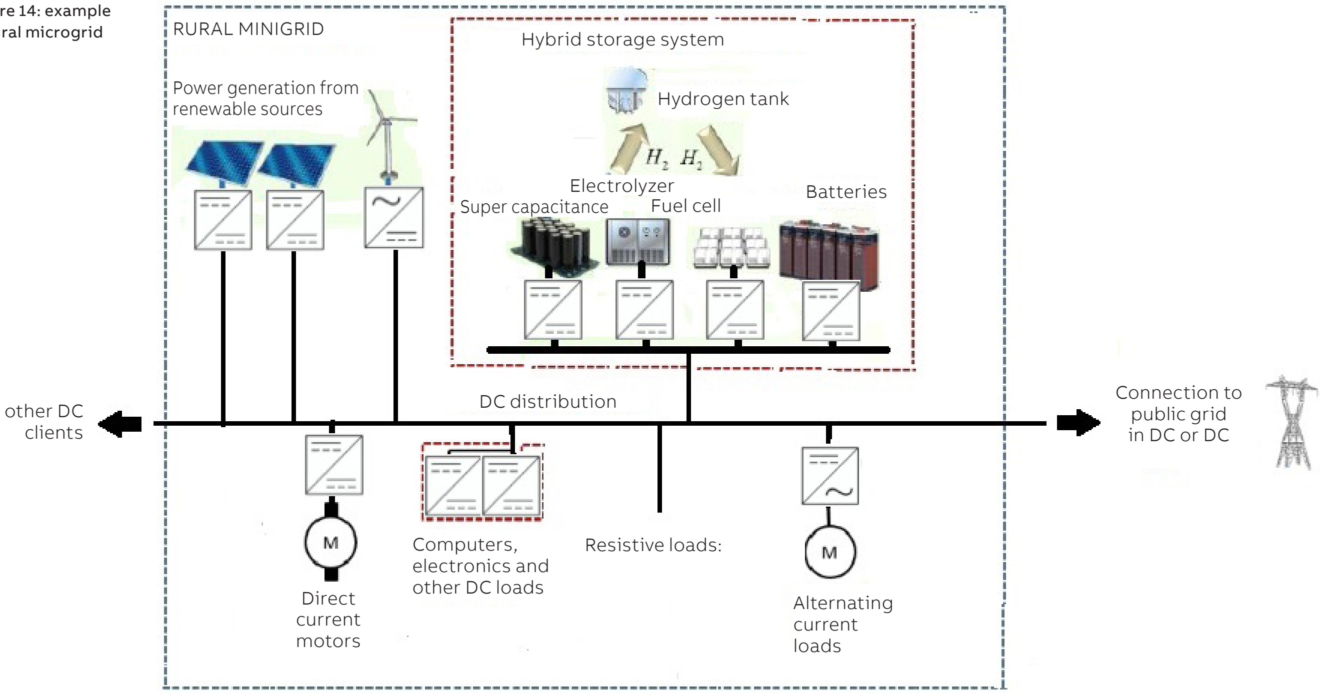
Figure 14: example of rural microgrid



Compared to an AC microgrid, the DC microgrid can lead to significant savings since losses are less thanks to the fact that fewer rectifiers are required.

Although they are designed to operate in the islanded mode, connection to the public grid can offer further guarantees as to the stability and continuity of the electric power supply. The cost of this connection would obviously depend on the length of the connection line and this could be especially critical in very extensive countries. The so-called Single Wire Earth Return (SWER, figure 15) is an already adopted AC solution. This system was developed in New Zealand during the '20's. By means of an isolation transformer, it allows the single-phase circuit to be closed by the earth, thereby saving on a conductor.

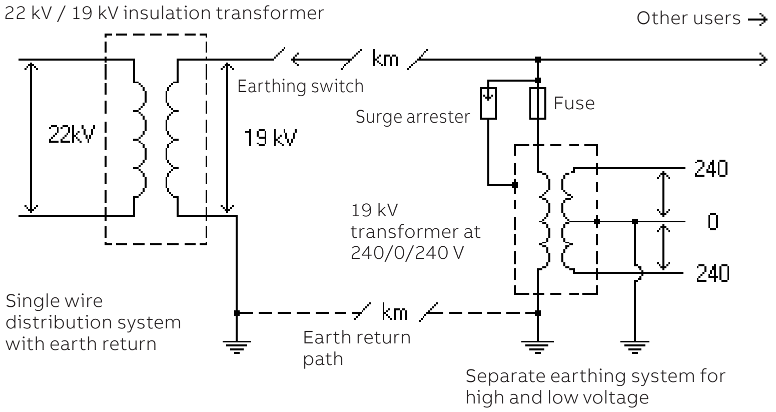


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Figure 15: circuit diagram for a SWER line

The typical voltage to earth ranges from 12.7 to 19.1 kV, covering tens or even hundreds of kilometers. When making an economic appraisal, one must first consider the economic viability of laying one single conductor and then the cost of the isolation transformers and other losses due to earth return resistance. Regarding this latter, one should bear in mind that in alternating current systems the return current follows, in the ground, the path taken by the electric line above even if the route is not linear. In addition, the layer at which it penetrates into the ground is proportional to $1/\sqrt{f}$, thus the theoretical section is proportional to 1/f while the resistance per unit of length is proportional to f. Over 200,000 km of such lines have been installed between New Zealand and Australia to date.

A direct current line could also be a practical method for connecting remote rural areas to the public grid thanks to the low losses offered by this solution (figure 16). Another advantage offered by the DC microgrid would be savings on the installation of an inverter and transformer compared to a simple DC/DC converter. Here again, use of direct current would allow a single conductor to be used by returning via ground. However, compared to the alternating current solution, current distribution in the ground is only determined by the resistivity of the various layers in the subsoil. Current penetrates at great depth if the connection points are very far from each other. Thus the current density is very small. In addition, the return current does not follow the line route but the path with the least resistance. Thus the ohmic resistance is small and practically equal to the resistance of the earth electrodes at the terminals.

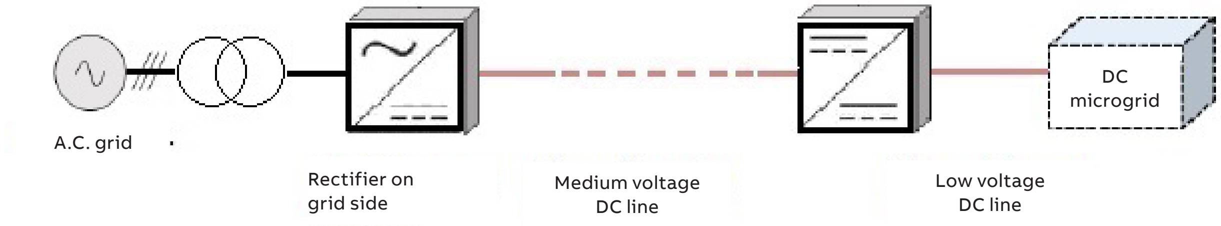

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Figure 16: connection line between AC network and DC microgrid

A DC distribution line involves considerable initial costs due to the static AC/DC converters. However, the investment improves as the length of the line increases and finally becomes extremely convenient. Proceed as follows to calculate this convenience:
We'll begin with a DC line with a single conductor. If the section of the conductor is A and its length l, the volume of that conductor is:

$$V = A \cdot l$$

The losses due to the Joule effect are:

$$p = R \cdot I^2 = \rho \frac{l}{A} \cdot I^2 = \rho \frac{l}{A} \cdot \frac{P^2}{U^2}$$

While the initial costs of the conductor are:

$$C_{DC} = \alpha \cdot A \cdot l = \alpha \cdot \rho \frac{l^2 P^2}{p_M U^2}$$

having fixed the maximum losses p_M and consequently calculated the section.

In the case of a three-phase AC system, the volume equals:

$$V = 3A \cdot l$$

And the losses:

$$p = 3R \cdot I^2 = 3\rho \frac{l}{A} \cdot I^2 = 3\rho \frac{l}{A} \cdot \frac{P^2}{3U^2 \cos\varphi^2} = \rho \frac{l}{A} \cdot \frac{P^2}{U^2 \cos\varphi^2}$$

Lastly, losses p_M being equal, the cost is:

$$C_{AC} = \alpha \cdot 3A \cdot l = \alpha \cdot 3\rho \frac{l^2 P^2}{p_M U^2 \cos\varphi^2}$$

The ratio between the costs of a three-phase AC line and a single DC line is therefore:

$$\frac{C_{AC}}{C_{DC}} = \frac{3}{\cos\varphi^2}$$

Thus the lower cost of the direct current conductors compensates, as the length of the line increases, for the higher initial cost until it actually becomes convenient compared to a similar alternating current solution. The next graph in figure 17 illustrates this condition in the qualitative mode.

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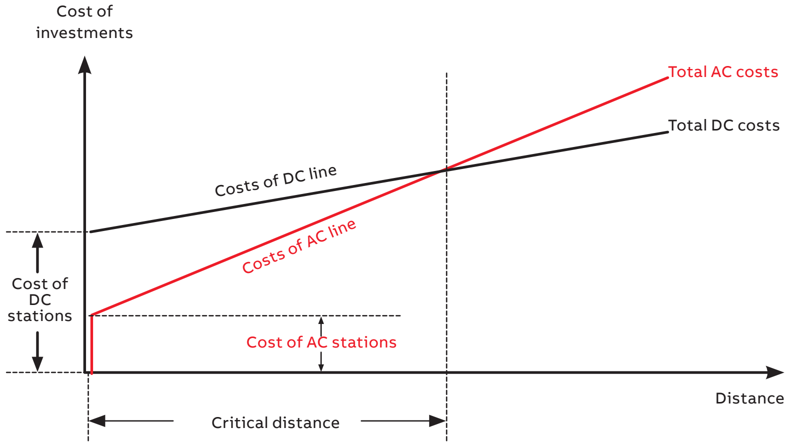
Figure 17: graph illustrating the cost-effectiveness of a DC connection line



3.5.3 Electrical ships

Ship installations have undergone considerable developments over the years. Safety is obviously of fundamental importance on ships, but other issues such as reducing consumptions and environmental impact have also acquired increasing priority.
The growing demand for enhanced safety imposes stringent requirements as to reliability and manoeuverability. In addition, reduced consumptions and lower environmental impact require greater efficiency when it comes to the propulsion system and, more generally, the technological systems on board, as well as reduced weights and volumes, and systems for the electrification of ships moored alongside the quay (Shore-to-ship, figure 18). This last solution allows ships to connect to the port electricity grid and, thus, to turn off their engines and stop producing harmful emissions, acoustic pollution and vibrations when berthed, especially as ports are often located in city areas.

The sum of all these requirements has encouraged the progressive electrification of ships. Initially built with a steam-powered propulsion system, the Queen Elizabeth II was the first ship to adopt al electric propulsion system in 1987. Thanks to this conversion, the ship's efficiency as to fuel consumption improved by some 35%, with savings amounting to 12 million pounds a year.

To get an indea of the power involved in a cruise ship, we can consider the “Costa Fortuna” as an example (figure 19). Built in the Fincantieri Shipyard of Genoa-Sestri on behalf of Costa Crociere, the Costa Fortuna is the largest cruise ship ever built for an Italian company.
The generation system comprises 6 alternators for an overall 90 MVA electric power (enough to supply a town of 50,000 inhabitants), connected to a 6.6 kV AC medium voltage distribution switchgear able to supply the hotel services and propell the ship. The actual propulsion system comprises two synchronous electric motors, each able to deliver 20 MW propulsion power at a rotational speed of 140 rpm and drive the vessel at a speed of 23 knots. The rotational speed of the electric motors is controlled by static drives at variable frequency allowing the entire speed range to be accurately regulated. To do this, ABB developed the Azipod propulsion system (figure 20) where the electric motor with propeller is encased in an pod-shaped enclosure with good hydrodynamic characteristics able to move through 360 degrees under the ship. The system has evolved into an industrial standard for the shipbuilding sector.

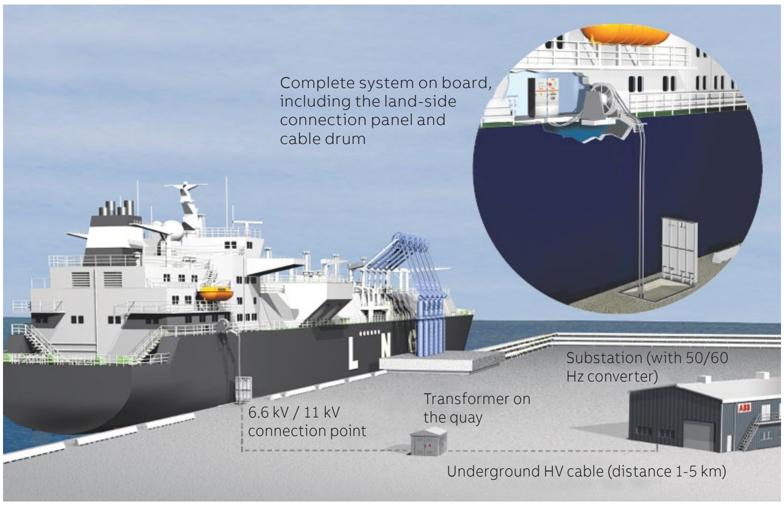


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Figure 18: shore-to-ship system

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Figure 19: modern ship with electric propulsion

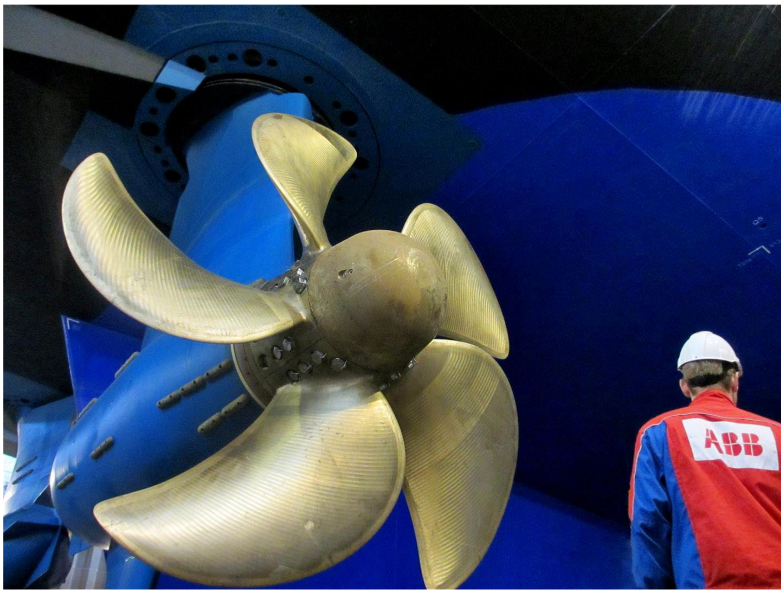

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Figure 20: Azipod propulsion system

This positionable propulsion system can drive and steer the vessel at the same time and reduces fuel consumption by up to 20% while ensuring accurate manoevrability without the aid of tugs.

According to Clarkson's Research, one of the most famous brokers among the principal shipping companies, the number of ships with electrical propulsion systems is increasing at the rhythm of 12 percent per year, three times faster than the world fleet.
If this is what is happening to the merchant fleet, military vessels are proceeding towards electrification at an even faster rate owing to the high electric power consumption of new weapons such as railguns and laser weapons, not to mention radar systems and increasingly sophisticated communication systems. The power required by the facilities on these ships now amounts to about one third of their propulsion power but according to forecasts, it will equal or even exceed this value in the future.

In view of the power involved, the well-defined limits and the load and generation distribution, the electrical systems on all-electric ships (AES) are microgrids to all effects.
However, problems concerning the use of alternating current were already observed in the case of the Queen Elizabeth II. For example, generators must function at constant speed, with loss of efficiency at different navigation speeds. Reactive power is generated and problems concerning quality can arise, such as phase unbalance and the introduction of harmonics; the transformers are extremely bulky and heavy; inability to supply large pulsating loads.

These problems are encourging researchers and engineers to look into the possibility of adopting a completely DC distribution network. Beside automatically resolving the electrical problems bound to the very nature of AC, DC networks do not merely use static converters (lighter and more compact) instead of transformers, but also allow the size and weight of the electrical distribution switchgear to be reduced. In addition, the drivers for feeding and adjusting electric propulsion are lighter and more compact (DC/AC instead of AC/AC). Examination of a specific case on a mega-yacht highlighted a significant convenience with DC, with 40% less weight and 80% less volume than the similar AC solution.
Moreover, use of variable speed generators (possible thanks to the decoupling allowed by the AC/DC converters) saves up to 15% fuel. DC distribution in military vessels allows the power supply to support the most sophisticated weapons and guarantees vital continuity of

service thanks to a more versatile architecture ensuring control over the aforementioned loads, over generation and the ESS (Energy Storage System).
Without ESS, the pulsed energy required by the new weapons would be supplied directly by the generators which, in order to do this, would have to be oversized.
When it comes to designing an electrical system, an AES possesses the same structure as a DC microgrid for landside installations. The powers involved are such as to require medium voltage distribution exceeding 6 kV DC (e.g.: 10 kV DC). Compared to microgrids for landside installations, a medium voltage ring solution is used in AES (a solution usually applied in Data Centers), divided into zones (DC Zone Electrical Distribution System or DC ZEDS) as illustrated in figure 21. These ZEDS are connected together and isolated from each other, and supply all the loads except for particularly important ones like radar and the propulsion motors, which are directly connected.

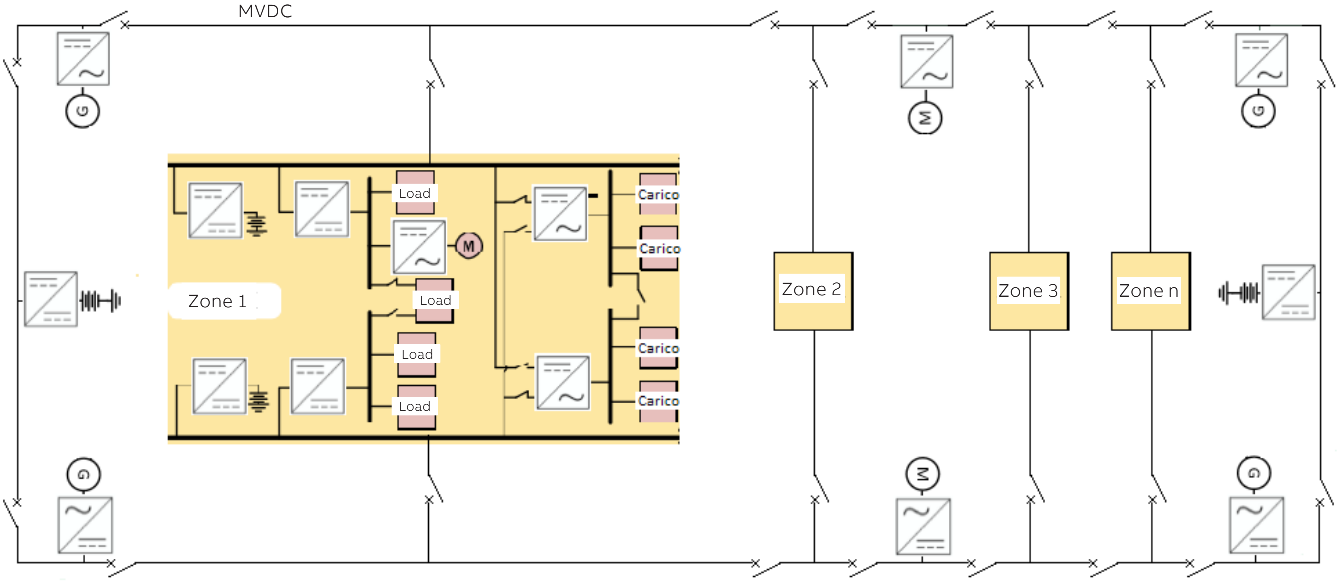

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Figure 21: circuit diagram of an AES

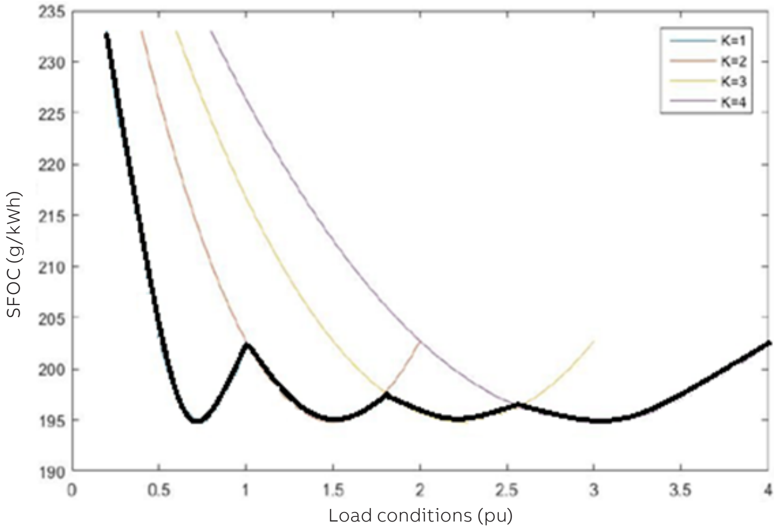

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Figure 22: example of consumption optimization for four diesel generators

Since the power is generated in alternating current by generators connected to diesel engines or gas turbines, rectifier converters are installed immediately on the load side of the generators. The main advantage of this configuration is decoupling of the generators, which can function at optimum speed as to efficiency in every load configuration without the problem of having to maintain a certain frequency. One of the solutions in large ships with AC distribution is to operate the diesel generators at their optimum speed and modulate their number so as to meet the power requirements of the loads (example in figure 22: Specific Fuel Oil Consumption (SFOC) on the basis of the load conditions, using 1 to 4 generators K).

However, this adjustment is slow and not very accurate and the generators may not always function at maximum efficiency, if only for short periods. Thus MVDC distribution appears to be the true solution if maximum fuel savings are to be achieved.

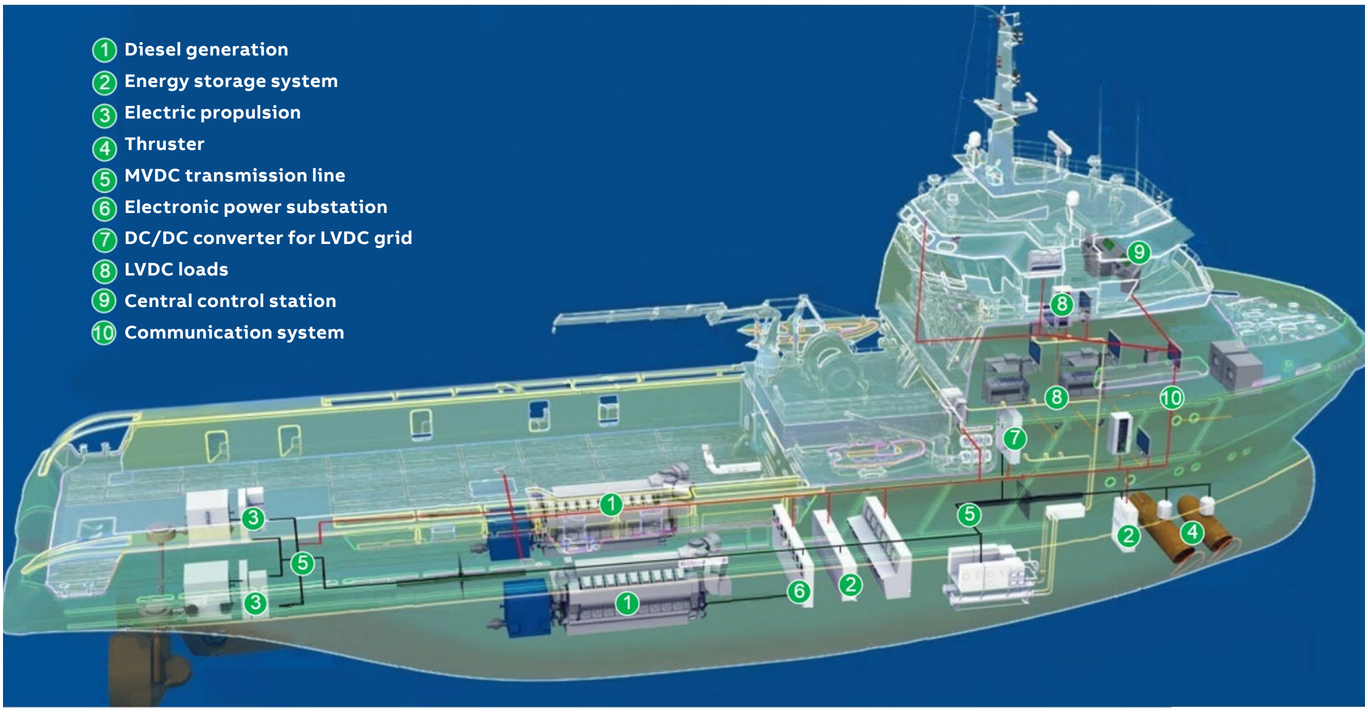
When MVDC power is distributed, there is no need to step up the voltage in order to supply direct loads. Initial rectification of the power produced by the generators is all that's required. In MVDC distribution, all the ZEDS are supplied in DC and converters change the voltage level or convert it into AC at the frequency required by the loads. In this latter case, transformers can be installed to lower the voltage level still further. UPS with DC/DC converters are installed on military ships near the pulsed power loads of modern weapons for the purpose of compensating the peak power demand and optimize the size of the generators.

Switchgear equipped with DC circuit-breakers are used for MVDC distribution. Circuit-breakers designed for railway applications could already be used for this sort of distribution even though, unfortunately, the maximum voltage level (3.6 kV) is modest for this purpose. On the other hand, there is a whole range of low voltage DC circuit-breakers available. Each zone could be supplied by each of the two switchgear in the distribution ring so as to guarantee maximum continuity of service. Figure 24 below shows an example of a tug with MVDC distribution.

As to fault conditions, although, on the one hand, static converters can limit the outgoing power thereby preventing serious damage to the loads, on the other, this situation can lead to critical conditions in the supply of loads that are not affected by the fault. To overcome the problem in microgrids, the tendency is to oversize the converters. This is not the ideal solution for on-board installations where space and weight are subject to limitations. Fault elimination by isolating the affected area and guaranteeing continuity in the other zones is of fundamental importance in large vessels. The availability of suitable protection devices, circuit-breakers and load disconnectors is a critical issue currently being addressed by major research and development initiatives. Similarly to other microgrids, reconfiguration after different load or fault conditions is extremely complex and needs a centralized hierarchical control system and an advanced communication system able to handle it.

Figure 23: diesel generator

Figure 24: ship with MVDC distribution



3.5.4 Data Centers

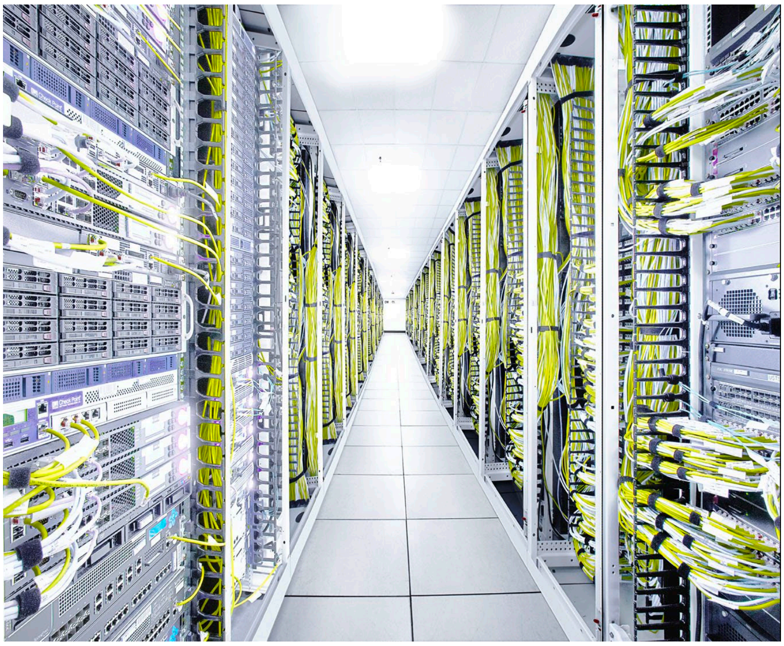


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Figure 25: inside a data center

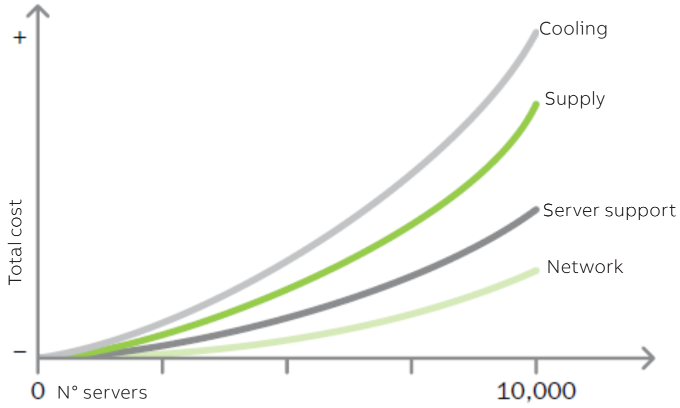

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Figure 26: types and distribution of loads in a data center

Nowadays, data centers (also known as server farms) contain most of the information required for the functioning of our societies. This means that the availability of data is absolutely the most important issue to face when the relative electrical system is designed. However, a second aspect, i.e. reduced consumption, is peremptorily emerging as the dimensions and, thus, the power required increase and the cost of electric power rises.
According to estimates, the overall cost of the power consumption of data centers for energizing and conditioning increased from 10 billion euros in 1996 to about 40 billion euros in 2010.
The typical loads of a data center are digital devices such as DC-powered computers and communication systems. The conditioning system is another important load in a data center, and the power required is on the increase in view of the progressive increase in the power of processors. In the current architecture where the distribution system is in AC, power suppliers, i.e. the numerous AC/DC converters with their typical 65 … 70% efficiency, also consume a large amount of energy (figure 26).

A typical data center is energized by two or more AC sources formed, for example, by two independent lines connected to the public grid and an emergency diesel generator. The typical supply voltage is 400 V AC. Then there are UPS for the purpose of ensuring maximum continuity of supply and 400 V AC distribution for powering the various digital systems, perhaps with further voltage reduction, and the conditioning system. As can be seen in figure 27, in this type of architecture there are at least three conversions, from AC to DC or vice versa, in order to obtain DC supply at the voltage value required by the electronic components.

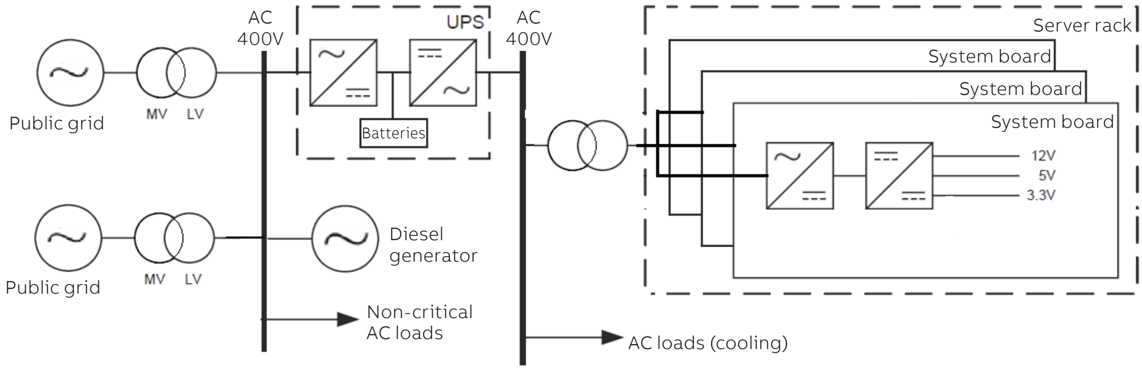


Figure 27: architecture of a data center with AC distribution system

Starting from the point of supply of the public grid, one can consider an overall 58% efficiency (figure 28).

Thus, by using latest generation UPS and improving the efficiency of the power suppliers (the weak point in the chain), it is theoretically possible to achieve approx. 80% efficiency.

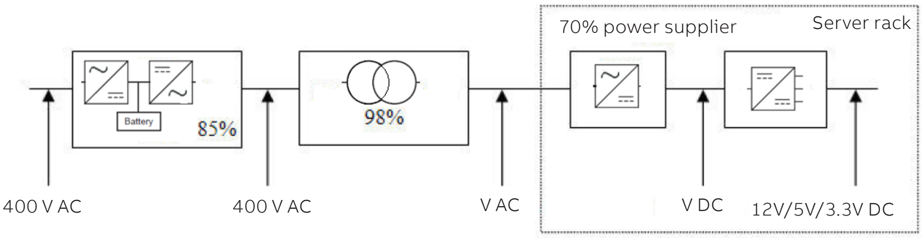


Figure 28: efficiency of the components of an AC supply system in a data center

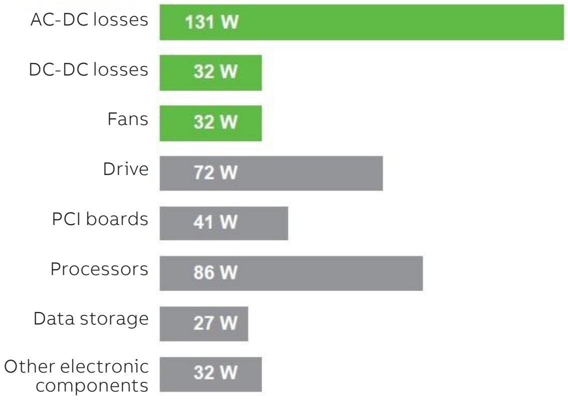


Figure 29: division of losses in a data center

In the example in figure 29, which illustrates a typical server board, the losses due to the power supplier account for 36% of the power consumption and the rectification stage actually accounts for 29%.
Given the predominance of digital loads, one might think that use of a direct current distribution system would optimize consumption and reduce the number of conversions. Figure 30 shows that compared to the AC distribution system, there is only one initial rectifying conversion.

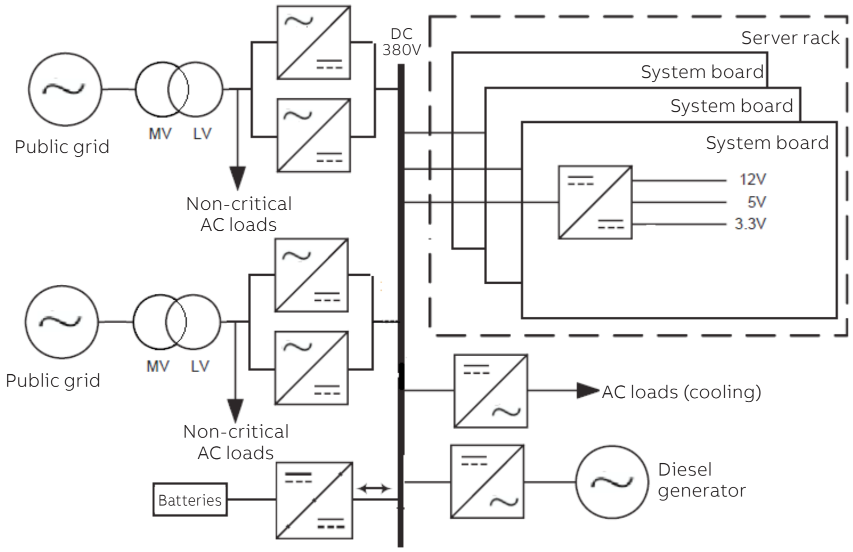


Figure 30: architecture of a data center with DC distribution isystem

Calculated from the public grid's point of supply through to the end consumer, the overall efficiency in this case, is 86%.

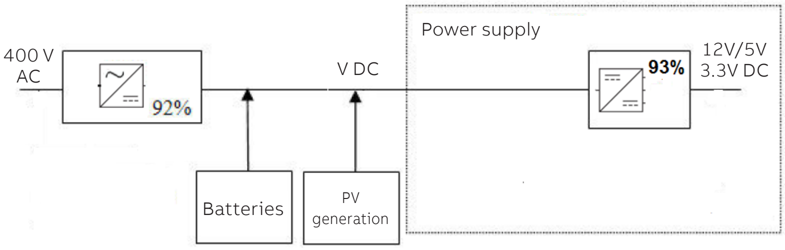


Figure 31: efficiency of the components of a DC supply system in a data center

Efficiency is thus in favour of DC distribution in Data Centers, although not to a very great extent. DC distribution by the actual Public Utility Company, first in MVDC and then in LVDC, could evidently make the difference, since it would also do away with losses due to the rectifier and thus raise the efficiency to 93%.

Generally speaking, from the reliability aspect, one could say that (for similar components), the fewer the components involved the better overall reliability becomes. Furthermore, rectifiers are generally less reliable than DC/DC converters since they are more complex. Consequently, DC distribution appears to be a better choice as regards reliability.

The installation of photovoltaic panels for local power generation could provide added impetus since DC distribution could save on the inverter. In short, as local generation increases, part of which directly in DC, Data Centers would become increasingly similar to DC microgrids able to function in the islanded mode, thus separately from the public grid.

3.5.5 DC industrial installations

The production process in certain industrial enterprises requires direct current, this either because it is required by the process itself or to reduce consumption as an alternative to a similar process in AC.

This is the case of certain processes in the chemical and steel industries.

The electro-winning process illustrated in figure 32 is commonly used for the electrodeposition of metals from ores that have been put in a solution via a preventive process commonly called leaching, during which soluble components are separated from a solid mass by means of a solvent. Electrorefining uses a similar process to remove impurities from a metal. Both processes use electrolysis. During electrolysis, current is passed from an inert anode through a liquid leach solution containing the metal, so that the metal is extracted as it is deposited onto the cathode.

In electrorefining, the anode consists of unrefined impure metal. The current passes through the electrolyte and the anode is corroded into the solution so that the electroplating process deposits refined pure metal onto the cathode. The most common electrowon metals are lead, copper, gold, silver, zinc, aluminum, chromium, cobalt, manganese, rare earths and alkali metals. For aluminum, this is the only production process employed. Many electroextraction systems are used for removing toxic (and sometimes valuable) metals from industrial waste.

During electro-winning or electro-refining, direct current is used by means of a static rectifier. Figure 33 illustrates the ABB solution for a copper or zinc electro-winning installation.

Figure 32: copper refining installation

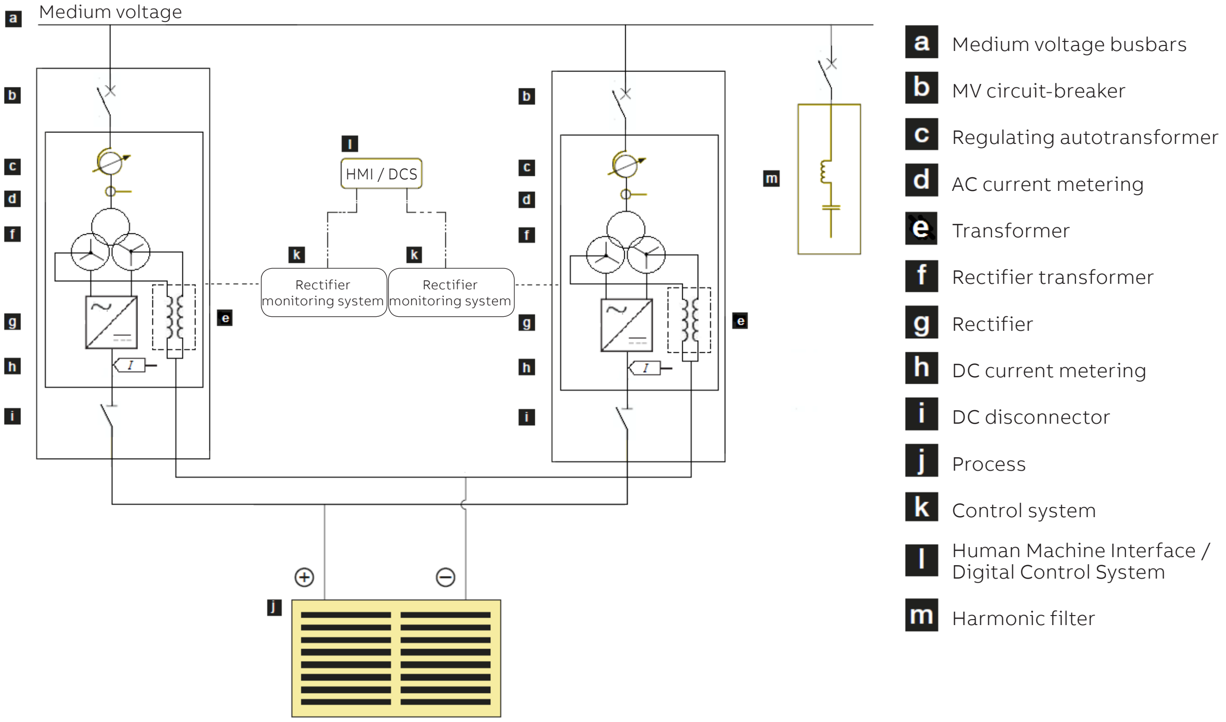


Figure 33: circuit diagram of an electrowinning system

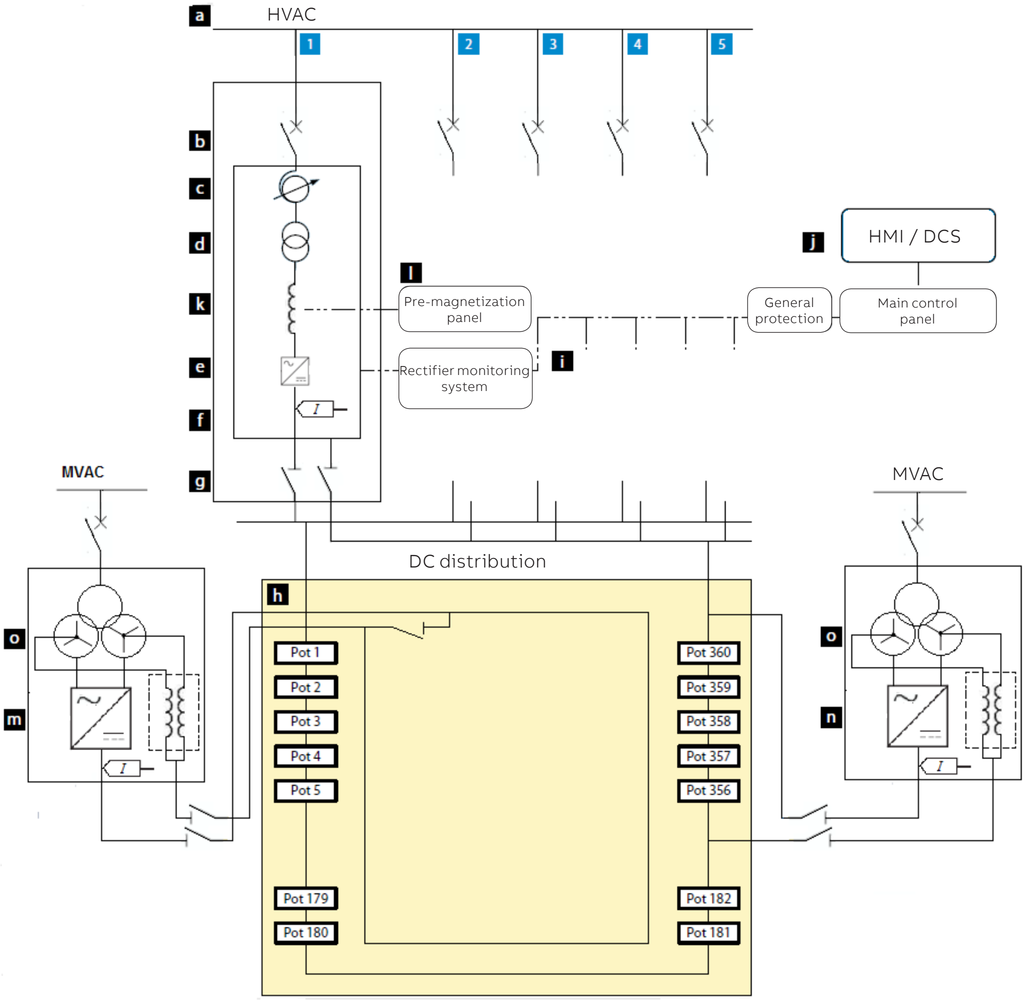
As can be seen, DC disconnectors are installed in the direct current part since the task of limiting the fault current is left to the static converter. The system is protected in AC by circuit-breakers for each riser.

Similar systems are used for the production of alkali-chlorides such as chlorine (CI2) and alkalis, sodium hydroxide (NaOH) and potassium hydroxide (KOH), again by means of electrolysis of a salt solution.

When it comes to aluminum (which is only extracted by means of electrolysis - figure 34), the relative production facilities are different, but only as to plant engineering. During the process, known as Hall-Héroult, the aluminum is produced in an electrolytic cell, where the electrolyte consists of a cryolite and alumina bath. Liquid aluminum is deposited at the cathode, which consists of a casing made of refractory material housing the electrodes. These installations are enormous and require a vast quantity of AC power, which is rectified into DC so as to supply a large number of cells.

Figure 34: aluminum production plant

The typical layout proposed by ABB as as follows:



a HV busbars
b HV circuit-breaker
c Regulating autotransformer
d Rectifier transformer
e Rectifier
f DC current metering
g DC disconnector
h Process
i Control system
j Human Machine Interface / Digital Control System
k Saturable reactances
l Pre-magnetization panel
m Ring rectifier
n Speed-up rectifier
o Double-star transformer with interphase transformer

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Figure 35: circuit diagram of an aluminium production facility

A real DC distribution system can be noted in this case. As in the previous situation, numerous DC disconnectors have been installed since the task of limiting the fault current is left to the static converter. Again, the system is protected in AC by circuit-breakers for each riser.

Electric arc furnaces are in a different category as to type of finished product and production process (figure 36).
When it comes to supply voltage, there are two types of electric arc furnace:

- alternating current (AC) electric arc furnaces. These are normally energized by three-phase

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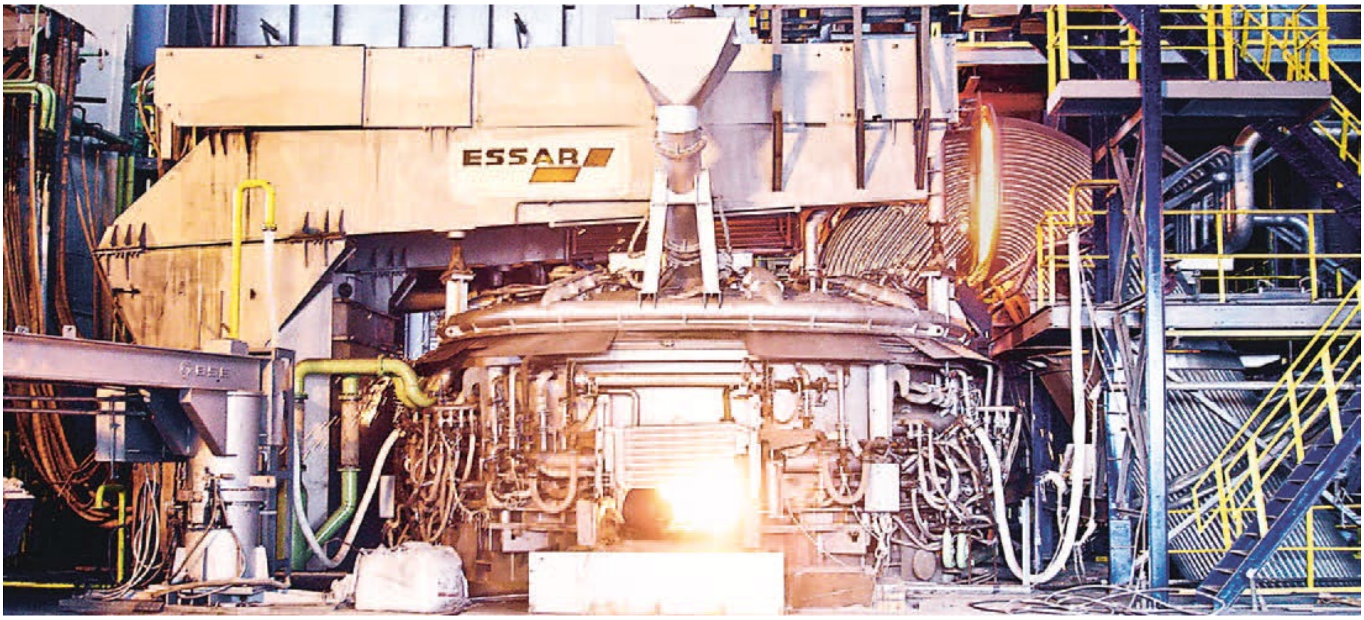
Figure 36: electric arc furnace



voltage and therefore feature three graphite electrodes installed in line (no longer used) or which form an equilateral triangle. The arc strikes directly between each electrode and the scrap metal. Once a certain level of molten metal has been reached, the electrodes bore into it and continue to produce heat while waiting for the entire load of scrap metal to reach melting point;

- direct current (DC) electric arc furnace: unlike the alternating current furnace, this type has one single electrode in the central position. The arc strikes between the electrode (cathode) and three "anodes" forming a triangle on the bottom of the furnace. This configuration forces the electric current to pass through the scrap metal, which melts.

The DC solution provides certain advantages:

- the arc is more stable, thus there is less wear on the electrode. The arc strikes at an angle of up to 30° on the molten metal and tends to turn continuously along the vertical axis owing to the effect of the magnetic field;
- enhanced efficiency when transferring power to the molten pool plus improved localization of the central “hot spot” compared to the three characteristic spots of the three-phase system;
- less **network disturbance.**

In addition, the presence of one single electrode simplifies the design of the crown of the furnace, the tilting mechanism and electric system (with the exception of the alternating-to-direct current rectifying system)
The typical circuit diagram with the control system proposed by ABB is illustrated in figure 37.

The advantage of being energized by a direct current public distribution grid for all these production systems with processes energized in DC via static rectifiers connected to the medium or high voltage AC public distribution grid should be evident. It would eliminate the need for transformers and rectifiers, which could be replaced by DC/DC converters so as to use a more suitable voltage level, consequently cutting down on investments and improving the overall efficiency. Local generation from renewable sources and storage systems able to optimize the supply, all in DC, would complete the conversion into DC microgrids. In systems where continuity of service is absolutely essential owing to the particular production processes, this would improve reliability and independence from the public grid.

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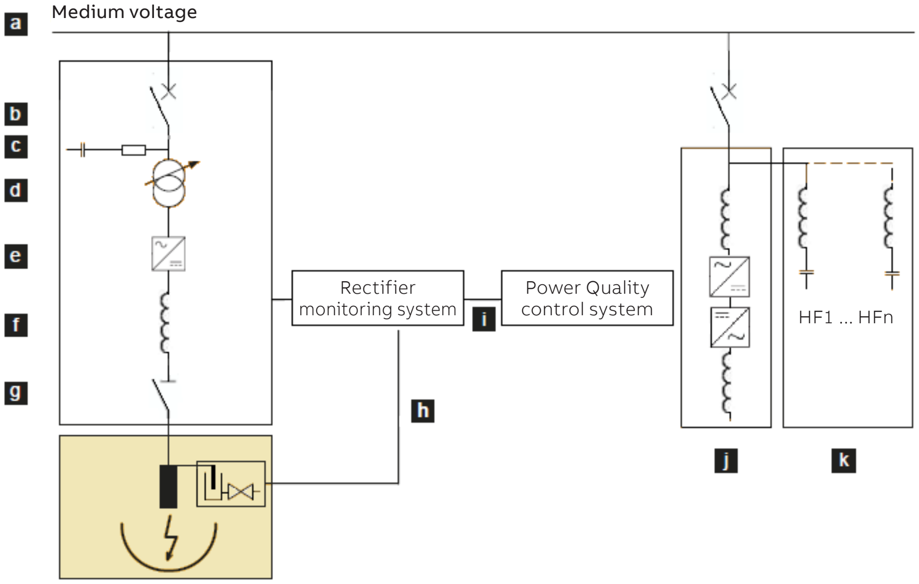
Figure 37: circuit diagram of an electric arc furnace



a MV busbars
b MV circuit-breaker
c Filter
d Transformer
e Rectifier
f Arc stabilizing reactance
g Disconnector
h Adaptive arc control
i Optical fiber connection
j Power Quality control system
k Harmonic filters

3.5.6 HVDC transmission lines

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Figure 38: HVDC conversion station

Comparison between a high voltage DC transmission line (HVDC) and a similar transmission line in AC shows that conduction losses due to the active power flow are less and those due to reactive power are actually nil. In just a few words, this explains the strong interest in HVDC installations and their rapid increase when the length of the line leads to a cost of losses able to balance the higher cost of the static conversion equipment.
The highest voltage normally used for an AC line is 800 kV. However, owing to the increased demand for transmitted power, 1000 kV and even 1200 kV have been considered for some installations. At over 800 kV, the power dissipated owing to losses through dielectric hysteresis is considerable. These losses are due to polarization phenomena, i.e. rotation and deformation of the molecules in the presence of a variable electric field, and depend on the intensity and frequency of the electric field itself. Their continuous movement heats the material by the same principle as a microwave oven.

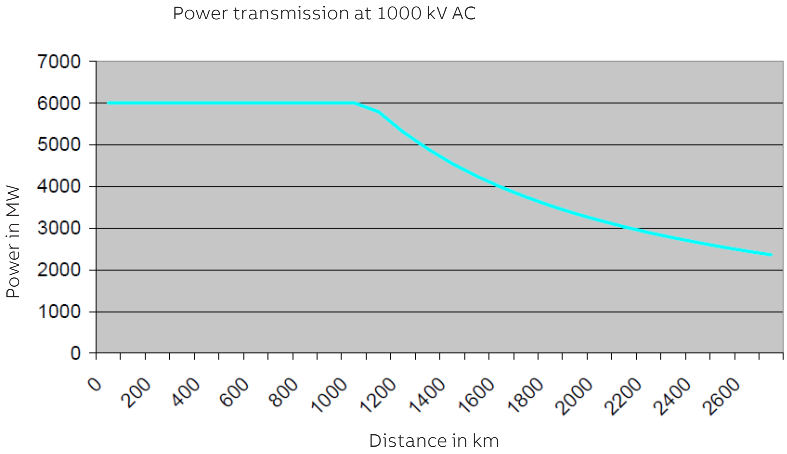

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Figure 39: capacitance / distance graph for a 1000 kV AC transmission line

Figure 39 illustrates the capacitance of a 1000 kV AC transmission line with 70% compensation and a 30 degree angle between the terminal points.

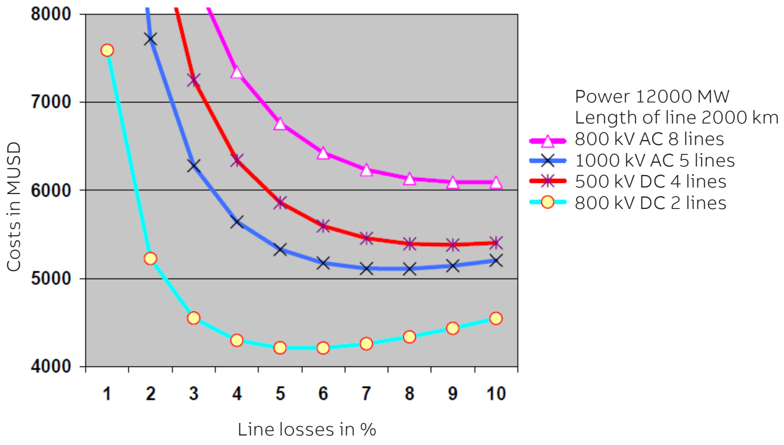


Figure 40: graph of investments in relation to percentage losses

It seems that even for long distances, over 1200 km, a 1000 kV AC line can begin to develop problems when transmitting high powers. When one assesses the investments required in relation to the losses (figure 40) for a line able to transmit 12 GW over 2000 km, one finds that the minimum investment is obtained with 800 kV DC lines. Generally speaking, the higher the power transmitted and the longer the line, the more an HVDC line becomes convenient.
When it comes to rated voltage, what is actually meant by AC and DC rated voltage must be clearly specified. In the first case, voltage refers to the root-mean-square value between two conductors, which more or less corresponds to the DC line-line voltage in terms of transmission capacity. Thus a ±500 kV HVDC line has double the capacity of a 500 kV AC line (figure 41).

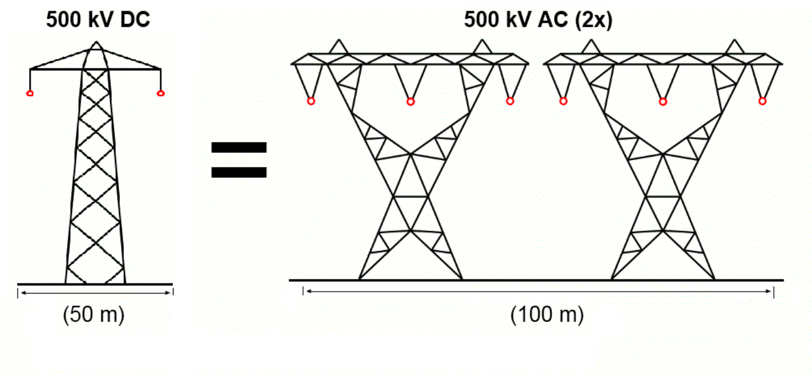


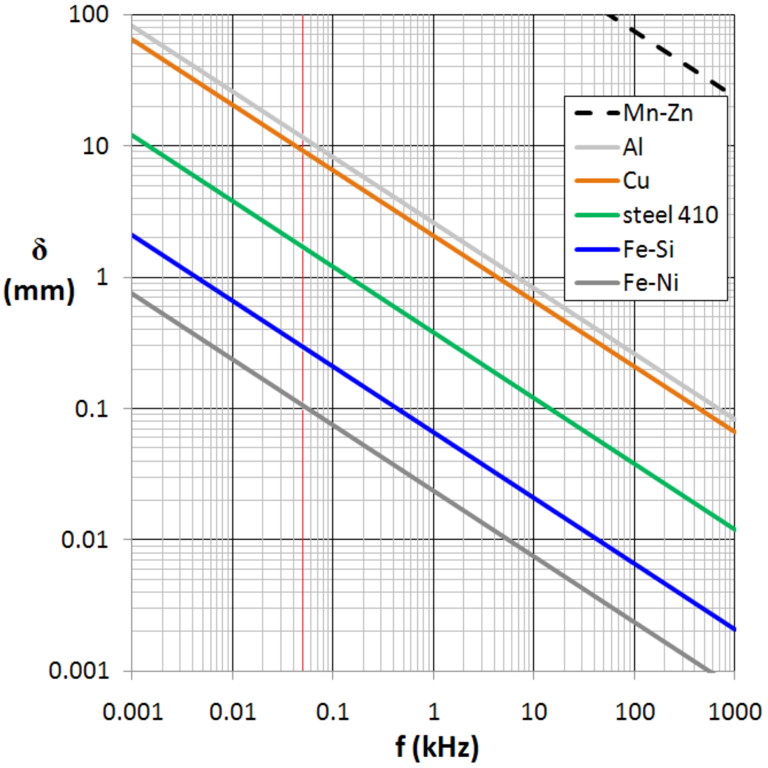
Figure 41: dimensional comparison between AC and DC transmission lines

Another advantage of DC lines is that they are not affected by the so-called skin effect, i.e. the tendency for alternating current to distribute itself within a conductor in an uneven way, with a greater density near the surface than in the interior.
The depth at which the current penetrates into the conductor, measured from its surface, is given by the following formula:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

and is about 10 mm at 50 Hz and 8.5 mm at 60 Hz (figure 42).

Figure 42: current penetration depth with respect to frequency



This means that there is higher electrical resistance in an AC conductor than in a DC one, which increases proportionally at the root of the frequency. For a conductor with diameter D and D>>δ:

$$\frac{R_{AC}}{R_{DC}} \approx \frac{D}{4\delta} = \frac{D}{4}\sqrt{\frac{\pi\mu f}{\rho}}$$

with: μ magnetic permeability of the conductor, ρ specific resistance of the conductor while lastly, ω is the angular frequency of the current, equal to 2πf.
Thus the result is greater power dissipation, applied current being equal.
If AC current is flowing through two or more nearby conductors, the magnetic field generated affects current distribution in these conductors and forces it to concentrate on the adjacent surfaces. This is called the proximity effect.

This means that in actual fact, the R_{AC}/R_{DC} ratio is higher than that produced by the skin effect alone. However, there are construction solutions able to mitigate the skin effect in AC systems, e.g. by installing several conductors in parallel, each with R_{AC}/R_{DC} =1 (thus at 50 Hz with a thickness of less than 15 … 20 mm), by plaiting the insulated wires together, bycoating the conductors with a layer of silver, by using two metals with the more precious one on the outside, or by making hollow conductors.

Whatever the case, the best solution is to use direct current, which is free from such effects.

If a cable transmission line must be used, e.g. undersea connections between islands and the mainland such as the one between Sardinia and mainland Italy, the high capacitance to earth, which is 50 … 100 times more than that of overhead lines, strongly limits the transmissible power in AC. In DC, the effect of capacitance in service conditions is nil and can only be sensed during transients, e.g. by slowing the voltage rate of rise at one end of the line from the moment in which the other end is powered. Figure 43 shows the world's first HVDC connection made in 1954 in Gotland, Sweden, with the contribution of ABB.

Lastly, a further advantage of the DC connection is decoupling between two connected grids that need not necessarily be synchronized (figure 44). Passage through a conversion into DC makes the two grids independent. In Japan, as many as three HVDC connections are used to connect two grids, 60 Hz in the western regions of Okinawa, Osaka, Kyoto, Kobe, Nagoya, Hiroshima and 50 Hz in the eastern regions of Tokyo, Kawasaki, Sapporo, Yokohama and Sendai, which are normally incompatible.

The cost of the converter substations and circuit-breakers in DC (figure 45) is thus the only factor that limits widespread adoption of HVDC lines. In actual fact, the same factor also limits the adoption of MVDC distribution grids.

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Figure 43: laying of an HVVDC connection in Gotland

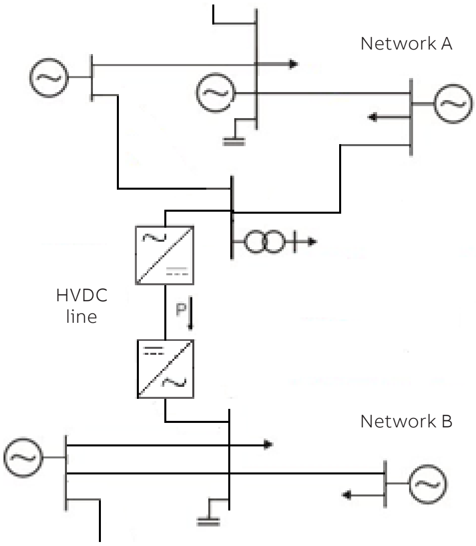

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Figure 44: diagram of the interconnection between two AC grids

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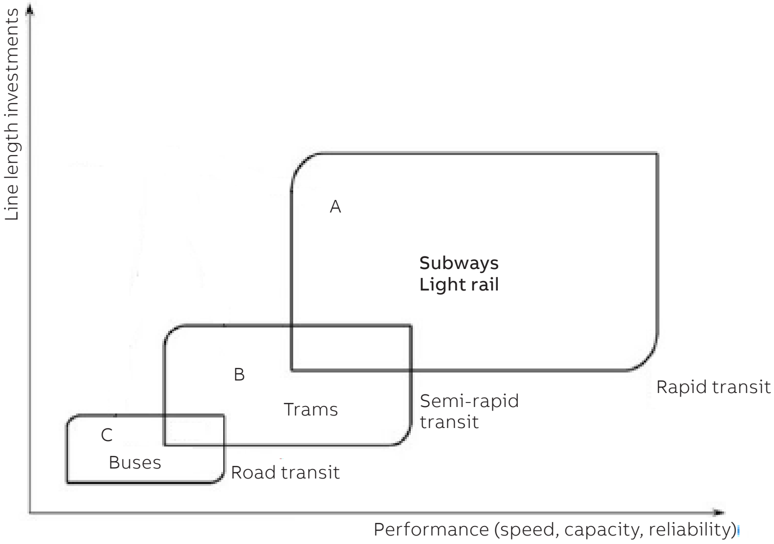
Figure 45: converters in an HVDC station

3.5.7 Electric traction

Figure 46: Railway application

The history of railway electric traction is recent yet intense. The first electric train was built in Berlin in 1879, but the potential of this system was immediately evident.
Tramways and suburban lines were the first to be electrified, since electric traction was not considered to be economically or technically valid for heavily trafficked railway lines. Thus, by the end of the 19th century, electric trams energized by low voltage direct current (typically 600 and 750 V DC) became widespread in the main cities of Europe and overseas.

Figure 47: graph of service investments for different transport systems



The first real electrification of a railway took place in America in 1895 when 600V DC was used. Switzerland was the first European country to follow suit by electrifying the Burgdorf-Thun railway at 750V AC. Not only was this the first railway line in Europe, but also the first experiment with AC traction. The threephase electric traction motor already offered certain advantages. It could function as a generator downhill while acting as an engine brake and supplying the trains with power uphill. After the first experiments with DC locomotives powered by batteries, energizing by a 3 kV DC direct current catenary was chosen in Italy.
Spain, Poland and Belgium also use this system in Europe. Other countries like Russia, the Czech Republic, Slovakia, Slovenia and Ukraine use both 3 kV direct current and 25 kV 50 Hz alternating current. The 25 kV AC single-phase system (50 Hz almost everywhere) is becoming the standard method for new railway electrification systems world-wide and has also been chosen in Italy and Spain for the new high-speed lines.
If the future of railway electric traction tends towards alternating current as a power supply, the outlook is more complex for the urban transport systems in medium sized and large cities. Urban systems comprise buses, trams, subways and light rail (figure 47).

These means of transport use low voltage direct current supply systems for safety reasons. To reduce pollution, buses are also evolving towards electric traction, with fast battery charging stations. For example, ABB has supplied the city of Geneva with flash-charging systems and on-board electric vehicle technology for 12 TOSA (Trolleybus Optimisation Système Alimentation) fully electric buses (e-buses) which will run on Line 23, connecting Geneva's airport with suburban Geneva (figure 48).

Figure 48: bus equipped with ABB TOSA

ABB will deliver and deploy 13 flash-charging stations along an urban transit bus route as well as three terminal and four depot supply stations. This is the same sort of system as the ones designed for private use, since it requires the installation of charging points with AC/DC rectifiers (figure 49).

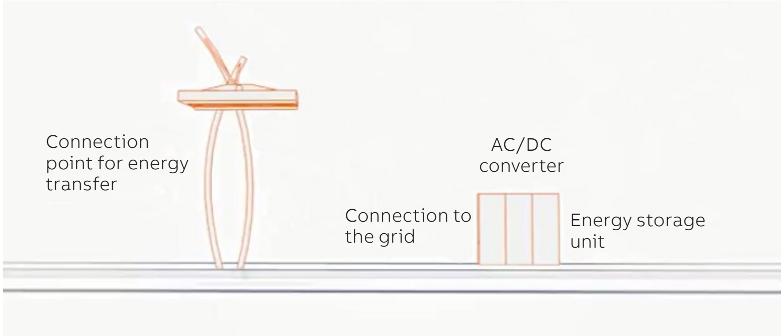


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Figure 49: ABB TOSA charging point

In tramway systems (figure 50), the electric line is much simpler than that of the railway: just one contact wire is used owing to the lower current consumption. The suspension system is also very simple with cross-span feeder cable suspension on poles or fixed by insulators to the adjacent buildings.

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Figure 50: example of a tramway

A recent development introduced for the purpose of reducing environmental impact in old town centers is that of discontinous supply with a third rail buried in the roadway which, for safety reasons, is only energized in the zone underneath the tram itself. In order to supply trams, electric power from the AC public distribution system is converted into direct current at between 500 and 750 Volts by means of conversion stations situated in various parts of the city and is then conveyed from these via underground cables to the power boxes of the lines.
Subway trains also use DC power by withdrawing voltage from a third rail via contact shoes. Compared to the overhead lines, this method does not need pantographs, thus the train can be narrower, ideal for long routes through tunnels. The construction costs are also lower since pile driving, installation of overhead lines and relative systems for stringing the line are not required. The third rail system is one of the oldest methods since it was already being used in 1890 in the London subway, the first in the world (figure 46). The maximum voltage used is 1200 V DC.
The return current normally runs along the rails where the train runs, but with some exceptions. For example, the London subway, the M1 line in Milan and certain lines in the Paris subway have another track for the return current. The disadvantage of this system is that it is unsuitable for high speed trains since the maximum operating voltage is too low. To get over the problem of low speed, some cities, especially megacities, have installed a light railway able to cover larger areas more efficiently. In this case, the supply system is similar to that of a railway with DC-powered overhead lines and maximum voltage up to 3 kV DC.
The structure of a light rail conversion station is illustrated in figure 51.

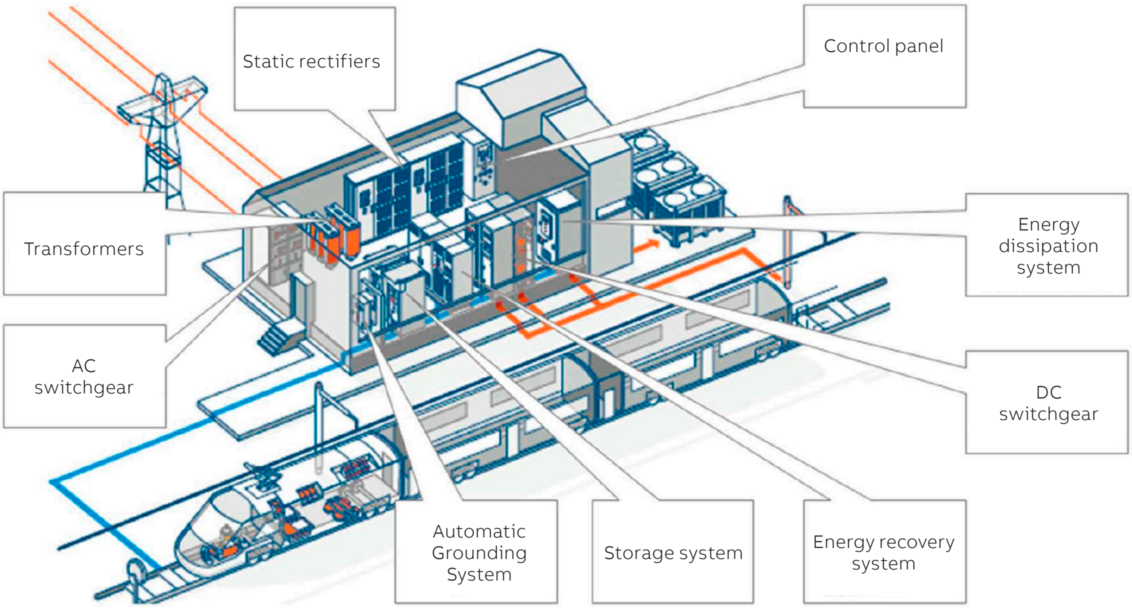

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Figure 51: railway substation for DC conversion

Recovery of the braking energy in trains is an issue of the highest concern since it saves on costs and enables train frequency to be increased on long distance routes. ABB has developed a range of specific high-efficiency products able to meet the individual requirements of different transport companies. A diagram of the complete braking energy control system is illustrated in figure 52.

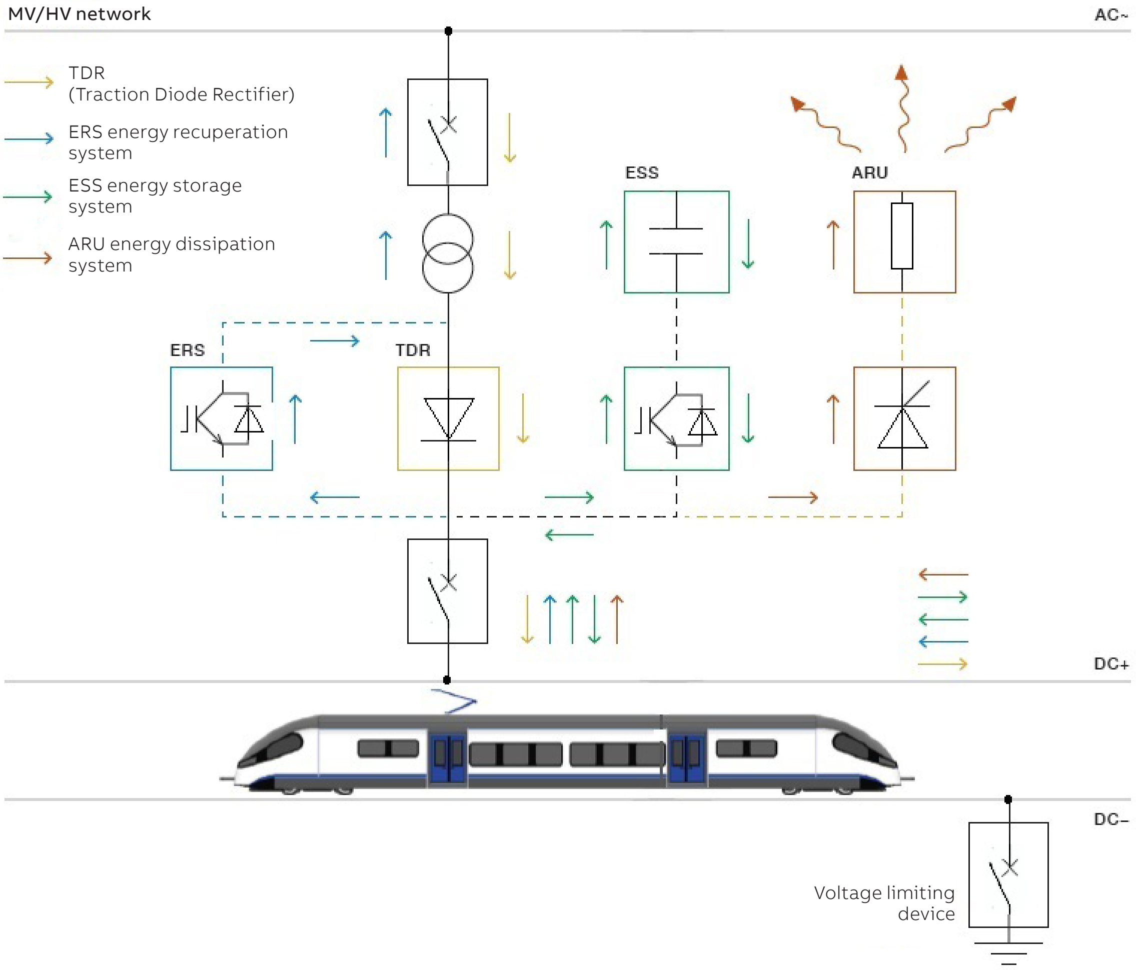

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Figure 52: diagram of the complete braking energy control system

ABB's ERS and ESS systems from the DC Traction Power Supply product range are shown in figure 53.

Figure 53: ABB's ERS (left) and ESS (right) systems

Use of direct current is not merely limited to the propulsion of vehicles. It is also used as a supply source for auxiliary circuits in the vehicles themselves. In these cases, accumulator batteries are installed as a source of backup power in the absence of the external source.

Subways and light rail transit need hefty investments but are able to transport large numbers of passengers without polluting, so the long-term benefits they provide far exceed the investments made.

In short, the urban transport system can be thought of as a direct current microgrid operating at different voltage values depending on the type of transport involved. Here again, supply by a DC public distribution grid would eliminate the need for transformers and rectifiers, which could be replaced by DC/DC converters so as to use a more suitable voltage level, thereby cutting down on investments and improving the overall efficiency.

4. Direct current interruption

4.1 Characteristics and problems

Direct current is a type of electric current characterized by a current flow whose intensity and direction remain constant over time. In other words, the electrons always flow in the same direction within the circuit. Consequently, unlike circuits with alternating current, it can be important to follow that direction, i.e. comply with the polarity. Unless they are properly protected, some types of apparatus can break down if connected with the wrong polarity. Since the current flow of alternating current reverses its direction at every half cycle and consequently crosses through natural zero, the electric arc which forms during the current interruption process quenches naturally the moment in which the current returns to zero.

Crossing does not occur with direct current and this makes the interruption process far more critical.

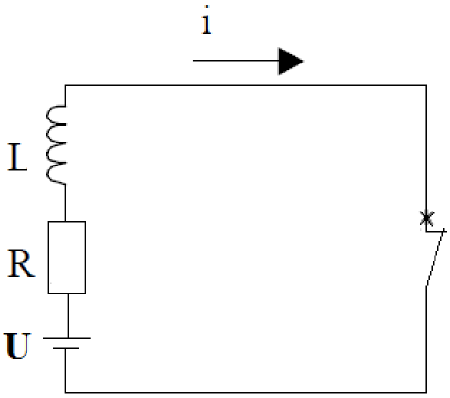

Figure 54: DC electric circuit with direct suppression

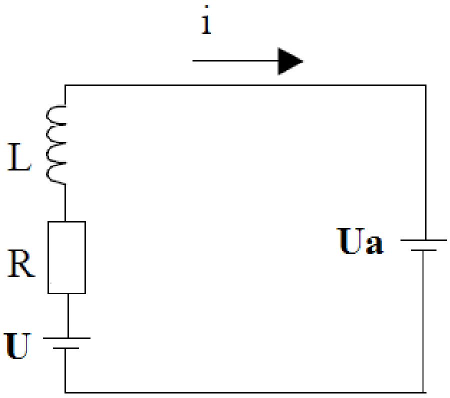

Figure 55: DC circuit during transient

4.1.1 Conventional interruption with direct current suppression

With reference to the circuit diagram illustrated in figure 54, the following direct current circulates when the circuit-breaker is closed:

$$i_0 = \frac{U}{R}$$

where U is the direct current applied, L and R are the resistance and inductance of the circuit. In addition, the energy stored in service conditions is:

$$W_0 = \frac{1}{2} L i_0^2$$

The moment in which the circuit-breaker opens, a transient caused by the appearance of arc voltage U_a is generated. This also introduces a voltage due to the presence of inductance L (figure 55). If the circuit-breaker is replaced by its arc voltage in the circuit, the applicable formula becomes:

$$U - R \cdot i(t) - L\frac{di}{dt} - U_a = 0$$

Now, we'll suppose that when the circuit-breaker opens the current remains constant until the instant the maximum U_a is reached, which we'll consider as t=0, and that this latter remains constant. In other words, we're talking about the application, in t=0, of a generator of step voltage U_a, which will disappear the moment t_a in which the current tails off.

Resolution of the differential equation gives:

$$i(t) = \frac{U - U_a}{R} + c \cdot e^{-t/\tau}$$

with τ=L/R.

The principle of continuity in inductance L is applied to calculate constant c, thus the current in instant t=0- must equal the current in instant t=0+.

Since: $i(0-) = i_0 = \frac{U}{R}$

and $i(0+) = i(t) = \frac{U - U_a}{R} + c$

the result is: $\frac{U}{R} = \frac{U - U_a}{R} + c$

lastly: $c = \frac{U_a}{R}$

The solution of the differential equation for t>0 is therefore:

$$i(t) = \frac{U - U_a}{R} + \frac{U_a}{R} \cdot e^{-t/\tau}$$

Since the second term of the equation tends towards zero, it follows that the current only crosses zero if U_a is higher than U (figure 56).

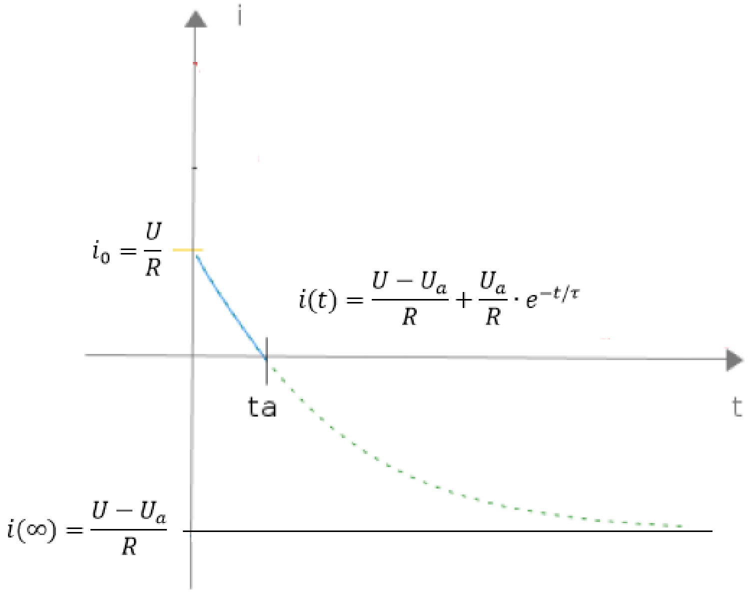

Figure 56: DC current trend with direct interruption

In this case, instant t_a represents the arcing time and is thus worth:

$$\frac{U - U_a}{R} + \frac{U_a}{R} \cdot e^{-\frac{t_a}{\tau}} = 0$$

$$-\frac{t_a}{\tau} = \ln \frac{U_a - U}{U_a}$$

$$t_a = -\tau \cdot \ln \frac{U_a - U}{U_a} = \frac{L}{R} \cdot \ln \frac{U_a}{U_a - U}$$

The energy dissipated by the arc can now be calculated as:

$$W_a = \int_0^{t_a} U_a \cdot i(t) \cdot dt = U_a \int_0^{t_a} \left(\frac{U - U_a}{R} + \frac{U_a}{R} \cdot e^{-t/\tau} \right) \cdot dt$$

Proceeding with the calculations, the result becomes:

$$W_a = U_a L \frac{U}{R^2} \left[\ln \frac{U_a}{U_a - U} \cdot \left(1 - \frac{U_a}{U} \right) + 1 \right]$$

Multiplying and dividing by U and bearing in mind that $U/R=i_0$ and that $W_0=1/2\ L\ i_0^2$ we can now write:

$$W_a = \frac{U_a}{U} \cdot L \cdot i_0^2 \left[\ln \frac{U_a}{U_a - U} \cdot \left(1 - \frac{U_a}{U} \right) + 1 \right] = W_0 \frac{U_a}{U} \cdot 2 \left[\ln \frac{U_a}{U_a - U} \cdot \left(1 - \frac{U_a}{U} \right) + 1 \right]$$

According to the theory expressed above, interruption will only be successful if the circuit-breaker is able to bring arc voltage that exceeds the rated voltage of the circuit into play and if it is able to support energy W_a (function of initial energy W_0 and, thus, of the inductance of the circuit, and ratio U_a/U).

Ratio W_a/W_0 normally varies from 1 to 1.5 and the lower it is, the easier interruption becomes. With reference to figure 57, which illustrates the real trend of a DC interruption, it appears evident that one of the methods for reducing fault current Isc and, thus, energy is to reduce, as far as possible, the time between the beginning of the fault and the instant in which the contacts start to separate (called t_s).

This assumption led to the development of high-speed circuit-breakers. The same figure shows how the interrupted current value also depends on time constant τ, thus on the parameters of the circuit in which the circuit-breaker operates. This is why manufacturers use DC breaking capacity in conjunction with the circuit's time constant limit values.

The limits of this application are evident: interruption in air is the ideal sort, since it is able to support high arcing voltage and can easily dissipate the energy. However, the voltage cannot rise too much as U_a must always be higher than U. This consequently leads to an increase in the size of the arcing chamber and is therefore not very cost-effective.

This type of DC interruption is widely used in low and medium voltage systems for railway and industrial applications up to 3600 V.
Other methods have been developed to overcome the limits described above. For example, one alternative is to force direct current crossing through zero by changing the parameters of the circuit, basically by inducing the appropriate amplitude oscillation.

There are two categories: self-induced (or passive) oscillation and forced (or active) oscillation.

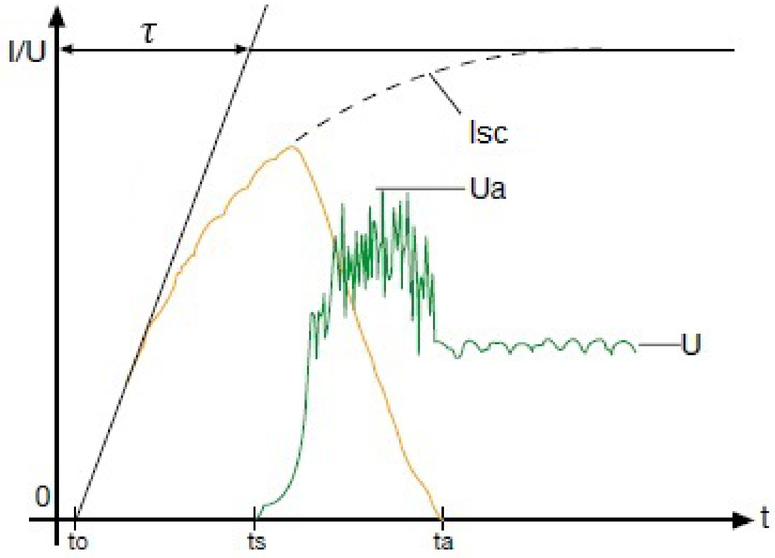

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Figure 57: trend of a DC direct interruption

4.1.2 Interruption with passive oscillating circuit

An LC circuit is connected in the passive oscillating circuit in parallel with the contacts of the circuit-breaker (figure 58).

Where:

I	is the circuit-breaker
II	is the switching circuit
III	is a zinc oxide protection varistor
L and R	are the inductance and resistance of the system
i	is the current to be interrupted
i_s	is the current in the circuit-breaker
i_c	is the current in the switching circuit
L_c and C_c	are the inductance and capacitance of the switching circuit
R_c	is the intrinsec resistance of the switching circuit
i_a	is the current of the protection circuit

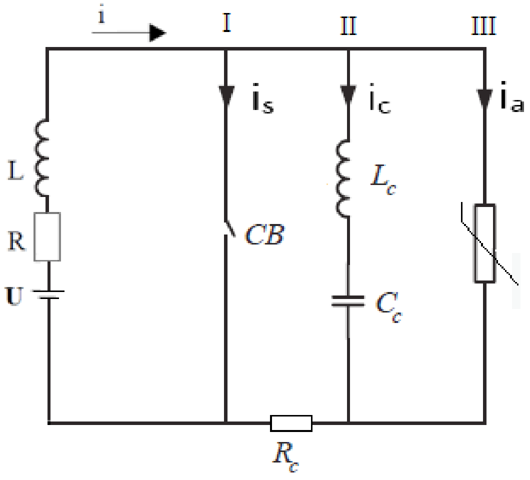

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Figure 58: passive oscillating interruption circuit

As described previously, when the circuit-breaker is closed, current circulates around the circuit through the circuit-breaker at the value of:

$$i = \frac{U}{R}$$

The circuit-breaker is replaced in the circuit with its arc voltage U_a upon opening (figure 59):

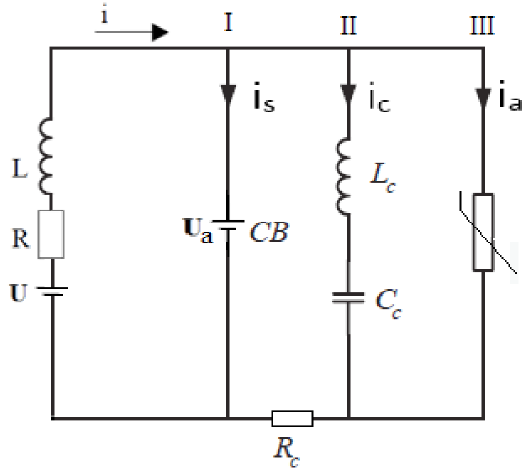

Figure 59: circuit of figure 58 with arc voltage

During the transient, we can write that:

$$U_L + U_C + U_R = U_a$$

thus:

$$L_c \frac{di_c}{dt} + \frac{1}{C_c}\int_0^t i_c\,dt + R_c i_c = U_a$$

for the sake of simplicity, R_c will not be considered, also because it is negligible; thus:

$$L_c \frac{d^2 i_c}{dt^2} + \frac{1}{C_c} i_c = \frac{dU_a}{dt}$$

Since the arc voltage is a non-linear function of the current, i.e. $U_a = f(i_s)$, we can write:

$$\frac{dU_a}{dt} = \frac{\delta U_a}{\delta i_s} \cdot \frac{di_s}{dt}$$

By substituting, the result is:

$$L_c \frac{d^2 i_c}{dt^2} + \frac{1}{C_c} i_c = \frac{\delta U_a}{\delta i_s} \cdot \frac{di_s}{dt}$$

Since, $i = i_S + i_C$ by expressing everything in relation to i_c and bearing in mind that i_0 is constant, the result is:

$$L_c \frac{d^2 i_c}{dt^2} + \frac{1}{C_c} i_c = \frac{\delta U_a}{\delta i_s} \cdot \left(-\frac{di_c}{dt}\right)$$

$$L_c \frac{d^2 i_c}{dt^2} + \left(\frac{\delta U_a}{\delta i_s}\right)\frac{di_c}{dt} + \frac{1}{C_c} i_c = 0$$

Term $\frac{\delta U_a}{\delta i_s}$ is dimensionally a resistance which we'll call R_a^{diff}

For the sake of simplicity, we'll assume that R_a^{diff} is constant. In addition, to obtain an oscillation, the roots of the quadratic differential equation must be complex and

thus $R_a^{diff} < 2\sqrt{\frac{L}{C}}$

Lastly, as initial conditions, we'll write $I_c(0)=0$ and $U_c(0)=0$ (capacitor discharged).

In the presence of these conditions, the solution of the differential equation is as follows:

$$i_c = \frac{U_a(0)}{\omega_c L_c} \cdot e^{-\frac{R_a^{diff}}{2L_c}t} \cdot \sin\omega_c t$$

If $\left(R_a^{diff}\right) < 0$ then i_c will oscillate at angular frequency $\omega_c = \sqrt{\frac{1}{L_c C_c} - \frac{\left(R_a^{diff}\right)^2}{4{L_c}^2}}$ and with increasing amplitude, thereby enabling the circuit-breaker to interrupt at first zero current. At this point, the entire current I is transferred to the switching circuit, thereby charging the capacitor C_c. Parallelly, the varistor limits the maximum voltage at the ends of the capacitor to the discharge voltage value.

The formulas above show that as the value of C_c increases, the oscillation frequency decreases until it disappears but the oscillation amplitude increases, thus a good capacitance value helps the interruption process. Vice versa, the increasing value of L_c not only causes the frequency to diminish but increases the time constant of the circuit $\tau = \frac{2L_c}{R_a^{diff}}$ and also decreases the oscillation amplitude $\frac{U_a(0)}{\omega_c L_c}$.

Thus it is useful for the value of L_c to be low. Another aspect to consider is that at high breaking current values R_a^{diff} is very low since it has a negative characteristic. So much so, the time constant is high. This means that quite some time can elapse before interruption occurs.

In conclusion, circuit-breakers based on this principle are unsuitable for interrupting high fault currents. Figure 60 illustrates the current trend obtained with L_c=40 µH and C_c=9 µF

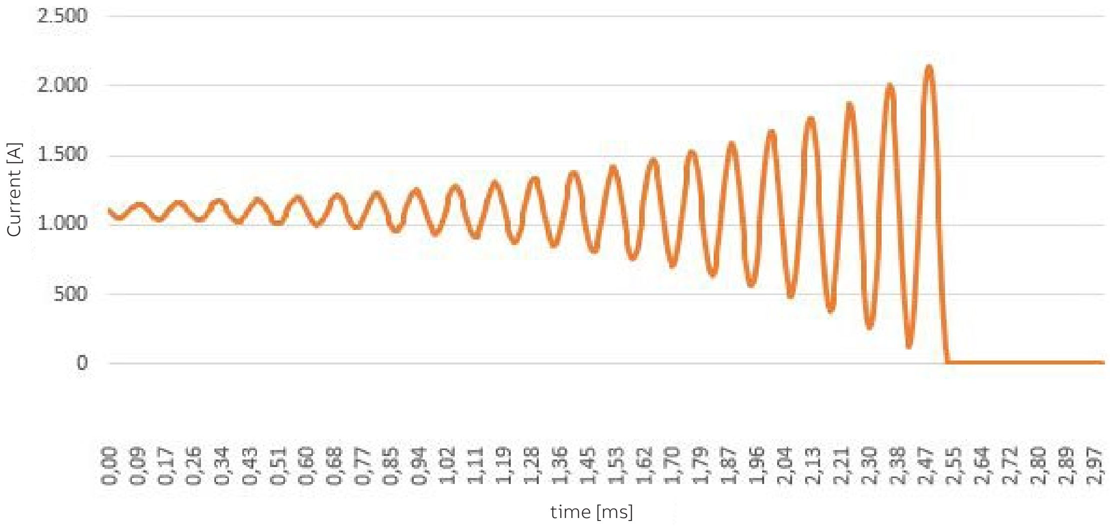

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Figure 60: current trend in a passive oscillating circuit

4.1.3 Interruption with active oscillating circuit

This type of interruption overcomes the problem of interrupting the high currents present in the case of passive oscillation circuits. The circuit is similar to the previous case, except for the fact that the capacitor is precharged.
The principle of this circuit-breaker is illustrated in figure 61:

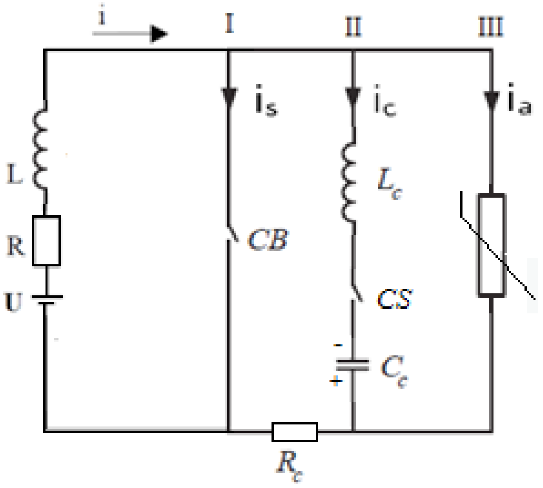

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Figure 61: active oscillating circuit

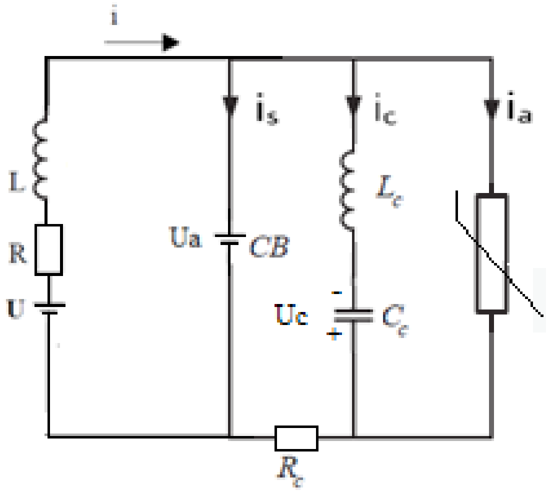

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Figure 62: circuit of figure 61 with arc voltage

Auxiliary contact CS connects the capacitor C_c and inductance L_c in series at the same time as the main circuit-breaker opens. In practice, the difference between active and passive interruption lies in the initial condition of the oscillating circuit since the capacitor is now charged, thus $U_c(0) \neq 0$. The relations in the previous section can all still be considered valid by adding the presence of a current of a sign opposite to the current that needs to be interrupted, the value of which depends on the charging voltage of the capacitor itself U_c, and which adds to the arc voltage U_a (figure 62).

Sure enough:

$$i_c = \frac{U_a(0) + U_c(0)}{\omega_c L_c} \cdot e^{-\frac{R_a^{diff}}{2L_c} t} \cdot \sin \omega_c t$$

A special capacitor precharging system is therefore required. One method is to use the actual line voltage.

4.1.4 Interruption with forced oscillation

This method of interruption is characterized by the presence of forced oscillation generated by an external source. As in the previous cases, this oscillation overlaps the DC current that needs to be interrupted so as to force it to cross zero.
A typical circuit is shown in figure 63:

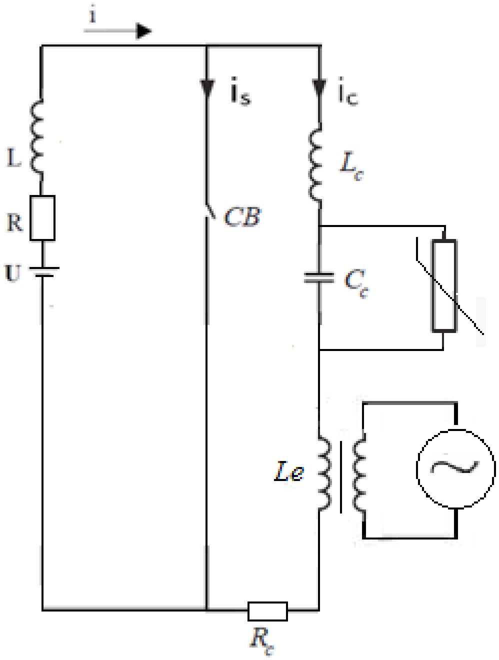

Figure 63: circuit with forced oscillation

The typical differential equation of this circuit becomes:

$$(L_c + L_e)\frac{d^2 i_c}{dt^2} + \left(\frac{\delta U_a}{\delta i_s}\right)\frac{di_c}{dt} + \frac{1}{C_c} i_c = Ue \sin \omega_e t$$

Where L_e is the leakage inductance of the transformer, U_e is the amplitude of external angular frequency source ω_e. Resonance is obtained when

$$\omega_c = \frac{1}{\sqrt{(L_c+L_e)\cdot C_c}}$$

The solution of the previous differential equation, with R_a^{diff} as a constant, is as follows:

$$i_c = \frac{U_a(0)}{\omega(L_c + L_e)} \cdot e^{-\frac{R_a^{diff}}{2(L_c+L_e)}t} \cdot \sin \omega t + U_e \frac{\left[\frac{1}{C_c} - \omega_e^2 \cdot (L_c + L_e)\right] \sin \omega_e t - \omega_e R_a^{diff} \cos \omega_e t}{\left[\frac{1}{C_c} - \omega_e^2 \cdot (L_c + L_e)\right]^2 + \left(\omega_e R_a^{diff}\right)^2}$$

The solution is formed by two terms: the first represents a weak oscillation with angular frequency ω_c given by L_c and C_c, as in the previous cases, and a second oscillation with angular frequency ω_e imposed by the external source.
When the current that needs to be interrupted is high and so long as R_a^{diff} becomes small, one can, with a certain approximation, write:

$$i_c = \frac{U_a(0)}{\omega(L_c + L_e)} \sin \omega t + U_e \frac{\sin \omega_e t}{\left[\frac{1}{C_c} - \omega_e^2 \cdot (L_c + L_e)\right]}$$

This expression shows that for $\omega_e = \omega_c$, the denominator of the second term becomes null, theoretically giving current with an infinite amplitude. Even in real conditions, one can see how convenient it is to increase the amplitude of the voltage of external source Ue and decrease frequency ω_e to obtain a greater contribution.

4.1.5 Interruption with parametric oscillation

This method of interruption is based on the parametric oscillation concept, i.e. an oscillator whose electrical parameters vary with a frequency near to the natural frequency of the circuit. From that viewpoint, this interruption principle differs from that of forced oscillation but is still based on using an oscillating current to overlap the direct current that needs to be interrupted.

The reference circuit is shown in figure 64:

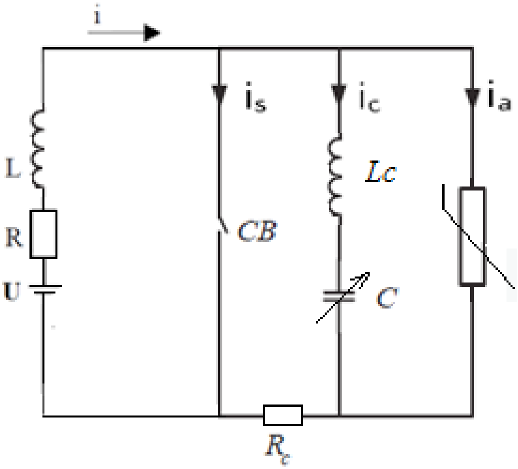

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Figure 64: circuit with parametric oscillation

As in the case of the passive oscillating circuit, oscillation initially begins after the circuit-breaker has opened, consequently causing an arc to strike. A “pumping” effect is obtained if the capacitance of capacitor C is varied with the same natural frequency as the oscillating circuit. In practice, the capacitor is first charged until the stored energy is at its maximum, then its capacitance C is reduced. For example, by simply moving the plates away if the capacitor is the parallel-plate type, thereby increasing the energy in the circuit. After this, with the capacitor discharged, the capacitance is brought to its initial value by nearing the contacts but this obviously occurs on an energy-being-equal basis. The process is therefore repeated twice per cycle. The oscillation is amplified until such time as the current crosses zero and the arc quenches. The inductance can be changed in a similar way by varying the position of its magnetic core. Using the relation already described for the passive oscillator gives:

$$U_L + U_C = U_a$$

But considering that the voltages on the components are now a function of the capacitor charge, the result is:

$$L_c \frac{d^2 q_c(t)}{dt^2} + \frac{1}{C} q_c(t) = U_a(t)$$

$U_a(t)$ can now be expressed as product of current $i_s(t)$ and resistance $R_a(i_s(t))$ which, in turn, is a function of the current $i_s(t)$ itself. In addition, given that $i_s(t) = i(t) - i_c(t)$, $i_s(t)$ is a function of the capacitance of the capacitor, the result at the end is a differential equation with variable parameters, very difficult to resolve analytically. Generally speaking, it is not easy to calibrate this type of circuit, since it only starts oscillating in the presence of certain circuit parameters.

4.1.6 Interruption with semiconductor technology

The intrinsic advantage of circuit-breakers based on this technology (figure 65) is that since they are ultra-fast, they can interrupt the current without waiting for it to cross zero.
These circuit-breakers normally use components like GTO, IGBT or MOSFET. These components can be connected in series or in parallel in order to comply with the rated current and voltage requirements. Absence of moving mechanical parts is another advantage of using this technology. This means that theoretically, the mechanical life of the circuit-breaker is infinite. However, one of the disadvantages is that faults can occur in the components owing to the high speed rate of rise of overvoltages dU/dt during opening operations and of overcurrents di/dt during closing. This is why a disconnector must be installed in series so as to ensure galvanic isolation.

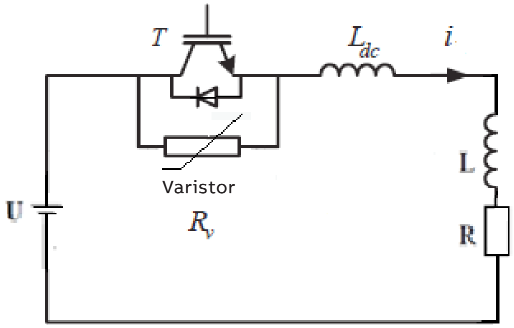
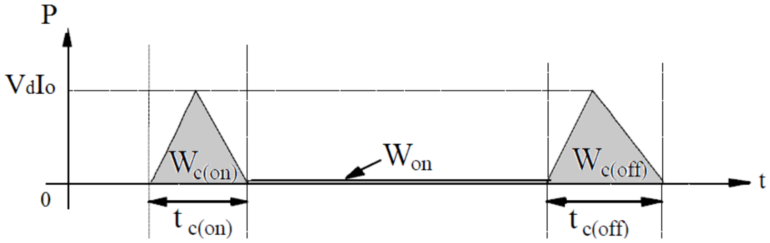


Figure 65: circuit with semiconductor switch

Another disadvantage is due to power dissipation owing to internal resistance. Besides the cost of losses, the heat produced can damage the component, thus suitable dissipation methods must be adopted.
One must consider that the losses in a semiconductor are both those produced during the conduction stage W_{on} and those produced during switching $W_{c(on)}$ and $W_{c(off)}$. The instantaneous losses during switching are higher than those of normal conduction, but only last for time $t_{c(on)}$ and $t_{c(off)}$ (figure 66). Thus these latter only become important if the switching frequency is high, as in the case of certain types of static converters. However, these events are not normal for circuit-breakers.

Figure 66: power dissipation according to conduction and switching time



With reference to the schematic circuit diagram, semiconductor T normally conducts and carries load current i. The current is interrupted the instant that interruption occurs t=0 and inductance L_{dc} limits the di/dt. The overvoltage at the ends of T is limited by the surge arrester to the value of discharge voltage U_s with $U_s=U+U_\Delta$. Supposing that the fault impedance is negligible, one can affirm that at instant t=0 there is:

$$U = U_s + L_{dc}\frac{di}{dt}$$

thus: $\frac{di}{dt} = \frac{U-U_s}{L_{dc}} = -\frac{U_\Delta}{L_{dc}}$

By integrating one obtains $i = I_0 - \frac{U_\Delta}{L_{dc}}t$

where $I_0=i(0)$ is the fault current. Interruption time t_a is the time at which the current extinguishes, thus:

$$t_a = \frac{L_{dc}}{U_\Delta}\cdot I_0$$

The energy absorbed by the surge arrester is:

$$W_s = (U+U_\Delta)\int_0^{t_a} i(t)dt = \left(\frac{U}{U_\Delta}+1\right)\cdot\frac{1}{2}L_{dc}I_0^2$$

Given that U_Δ is much smaller than U, it means that W_s is normally larger than the energy stored in inductance L_{dc} alone, which is $\frac{1}{2}L_{dc}I_0^2$ and that the difference increases as voltage U increases. Thus, the higher the rated voltage, the larger the surge arrester must be. From another viewpoint, once the application has been chosen and t_a and I_0 have been entered, the only parameter that can be modified is inductance, which changes the time constant of the current and relates to the discharge voltage of the surge arrester. A shorter interruption reduces power dissipation in the surge arrester but requires that this latter be sized for a higher voltage. On the other hand, an increase in the level of protection of the surge arrester involves a higher rated voltage for the circuit-breaker, thereby increasing the cost.

4.1.7 Interruption with hybrid technology

This method is based on the integration of a mechanical circuit-breaker with electronic devices, as illustrated in figure 67. The main components of a circuit-breaker based on this principle are: mechanical circuit-breaker, static circuit-breaker in parallel with the former and isolating disconnector in series with the previous two. The basic solution is illustrated in the figure below:

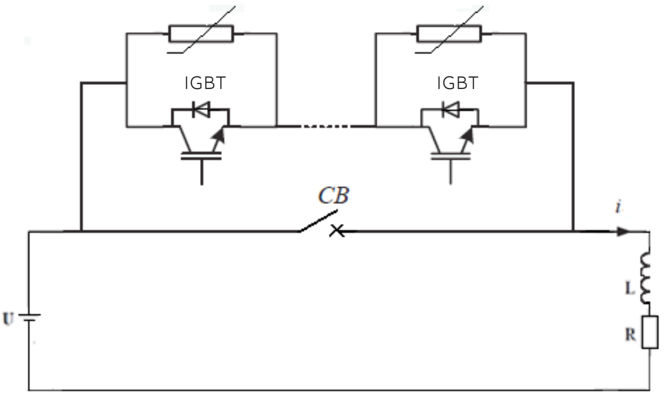


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Figure 67: interruption circuit with hybrid technology

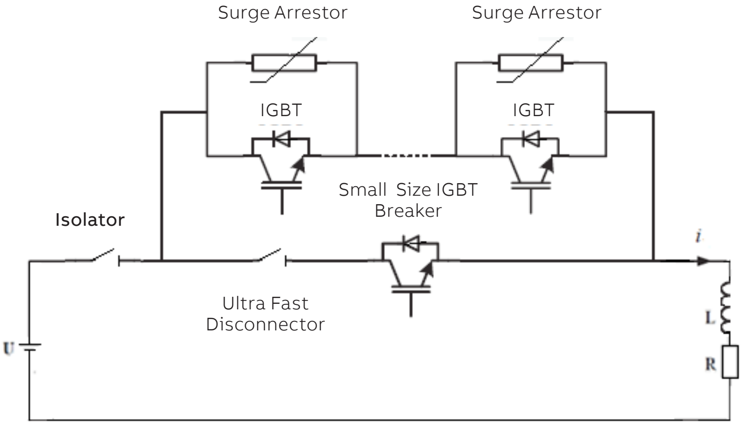

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Figure 68: diagram of hybrid circuit-breaker with static and mechanical device in series

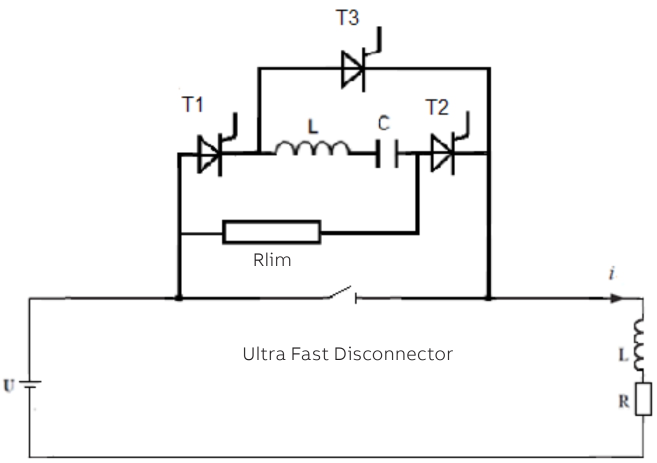

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Figure 69: diagram of a hybrid circuit-breaker with current pulse

In this case, a mechanical main breaker is installed in parallel with the static circuit-breakers. Arc voltage U_a created when the contacts separate must not (as in the direct current suppression breaker) return grid voltage U to zero, but merely create a voltage capable of switching the current in the branch with the static breaker switch. Once the arc has quenched and the contacts are completely open, the current is returned to zero by the static circuit-breaker.

In a second variant, the mechanical circuit-breaker is equipped with a static device in series with the first (figure 68). As in the previous case, the parallel branch consists of a series of static circuit-breakers. Typically, the static device in series in the main branch is an IGBT. The purpose is just to speed up switching towards the secondary branch in parallel by rapidly introducing a high voltage. The number of IGBTs required for this operation is therefore modest. Consequently, the losses and voltage drops that occur in the main branch during the entire conduction period are low.

Operation is similar to that of the previous circuit-breaker. During normal operation with the disconnector closed, current flows through the main branch towards the low-loss static device and mechanical disconnector itself. As soon as a fault occurs in the DC circuit, the auxiliary circuit-breaker with IGBT acts by rapidly switching the current in the secondary branch and allowing the high-speed disconnector to open practically without current.
At this point, the current is interrupted by the main static circuit-breaker. This configuration is used by ABB for its DC hybrid circuit-breaker.
A variant to the two hybrid circuit-breakers described above consists in creating a switching circuit that introduces a current pulse able to return the fault current to zero and allow the high-speed disconnector to open (figure 69).

After this, the current is switched to the limiting resistor and the capacitor is recharged. Negative voltage is thus applied to the thyristors, which are then able to interrupt the current.
The trip times of this second solution are evidently slightly longer than those of the first two variants described.

4.2 State-of-the-art of medium voltage DC circuit-breakers

4.2.1 ABB medium voltage air-insulated circuit-breakers for railway applications

ABB's DCBreak DC circuit-breaker is extremely light and compact, thus suitable for use on trains (or rolling stock), tramways, subways and urban and regional light railways (figure 70). These circuit-breakers are also based on the direct current-suppression principle described in section 4.1.1.

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Figure 70: ABB DCBreak circuit-breakers for applications on trains

In these applications, the weight and volume of the circuit-breaker are obviously fundamental requirements for their use. Maintenance is also an important issue and particular care has been taken to design these breakers so that the components most subject to wear, such as the arc chute and contacts, can be easily replaced without having to disassemble the entire circuit-breaker, the body of which is securely fixed to the structure of the locomotive. These circuit-breakers conform to standard IEC 60077-3 Railway applications – Electric equipment for rolling stock – Part 3: Electrotechnical components – Rules for d.c. circuit-breakers.
Section 4.1.1 describes how the interrupted current value also depends on time constant τ, thus on the parameters of the circuit in which the circuit-breaker operates.

—
Table 2: nominal time constants

Rated operational voltage U_e **[V]**	900	1800	3600
Time constant T1 (minimum) (ms)	0	0	0
Time constant T2 (ms)	15	15	15
Time constant T3 (ms)	50	40	30
Time constant T4 (ms)	150	100	50

The DC making and breaking capacities must be tested at the short-circuit time constant values given in table 2, in accordance with standard IEC 60850 Railway applications – Supply voltages of traction systems.

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Table 3: standardized voltages for DC railway applications

Electrification system	Lowest non-permanent voltage U_{min2} V	Lowest permanent voltage U_{min1} V	Nominal voltage U_n V	Highest permanent voltage U_{max1} V	Highest non-permanent voltage U_{max2} V
DC (mean values)	500 1000 2000	500 1000 2000	750 1500 3000	900 1800 3600	1000 1950 3900

The rating for this circuit-breaker ranges from 900 to 1800 V DC (table 3), rated current values up to 1500 A and 30 kA breaking capacity.

4.2.2 ABB hybrid circuit-breakers

The operating principle of this circuit-breaker is described in section 4.1.7. This particular circuit-breaker was designed for protecting HVDC lines. Illustrated in figure 71, the circuit-breaker comprises a load commutation switch (or LCS) in series with an ultra-fast disconnector (or UFD). The main circuit-breaker with semi-conductors consists of several sections equipped with surge arresters, sized for the maximum voltage and for the full breaking capacity envisaged. Vice versa, the LCS is sized for lower voltages and energy.

The ABB hybrid circuit-breaker was designed for 9.0 kA DC breaking capacity, 320 kV DC voltage and 2,000 A rated current. The breaking capacity depends solely on the size of the main static circuit-breaker. Ultra-fast disconnector UFD was designed for voltage exceeding 1.5 p.u. considering the voltage transients during switching.

Each HVDC compartment (figure 72) contains four layers of semiconductors and is equipped with surge arresters so as to limit the maximum voltage on the compartment during interruption to a specific value.

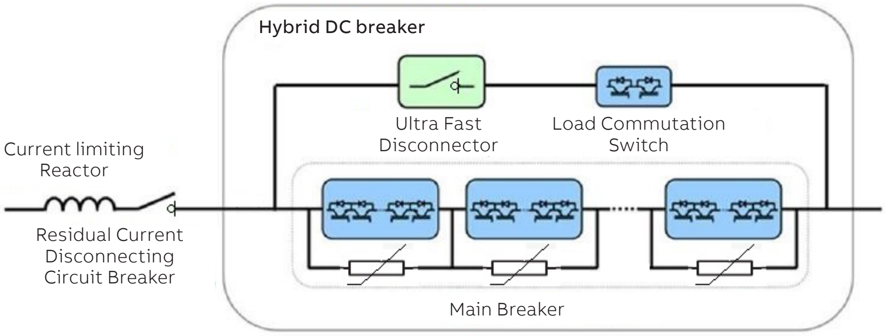

Figure 71: schematic diagram of the ABB hybrid circuit-breaker

Breaking speed is of fundamental importance in these applications since faults must typically be extinguished within 5 ms. The first reason for this is to prevent disturbance from being created in the conversion stations, the second is to reduce stress and, thus, the size of the actual circuit-breaker so as to also cut costs. Long breaking times require a higher breaking capacity, while the associated surge arrester would have to be oversized to an even greater extent.

Each layer consists of 20 IGBT connected in series. Owing to the high di/dt, accurate mechanical design engineering was required in order to obtain a very low inductance. This was achieved by using compact IGBT layers with 4.5 kV rated voltage. The IGBT gates are optically controlled to make interruption independent of disturbance from the grid.

Cooling systems are not required since the rated current does not pass through the semiconductor compartments of the main circuit-breaker.

It is sufficient to consider the rated voltage requirement when sizing the LCS. Regarding the rated current, other modules may have to be connected in parallel while modules in series would increase the reliability. A 3x3 matrix for each current direction was used for this project. A cooling system was required since the LSC continuously carries rated current, even though the losses are modest (tens of kW).

Figure 73 illustrates a break at 9 kA DC, which is the limit with the present generation of semi-conductors. A 250 µs delay time will be noted (due to opening of the LSC) and 2 ms delay due to opening of the UFD. As will be seen, the total break time 5 ms.

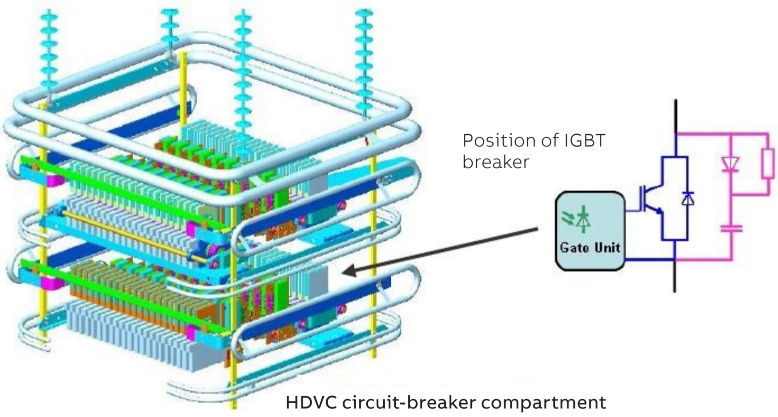

Figure 72: HVDC compartment of ABB circuit-breaker

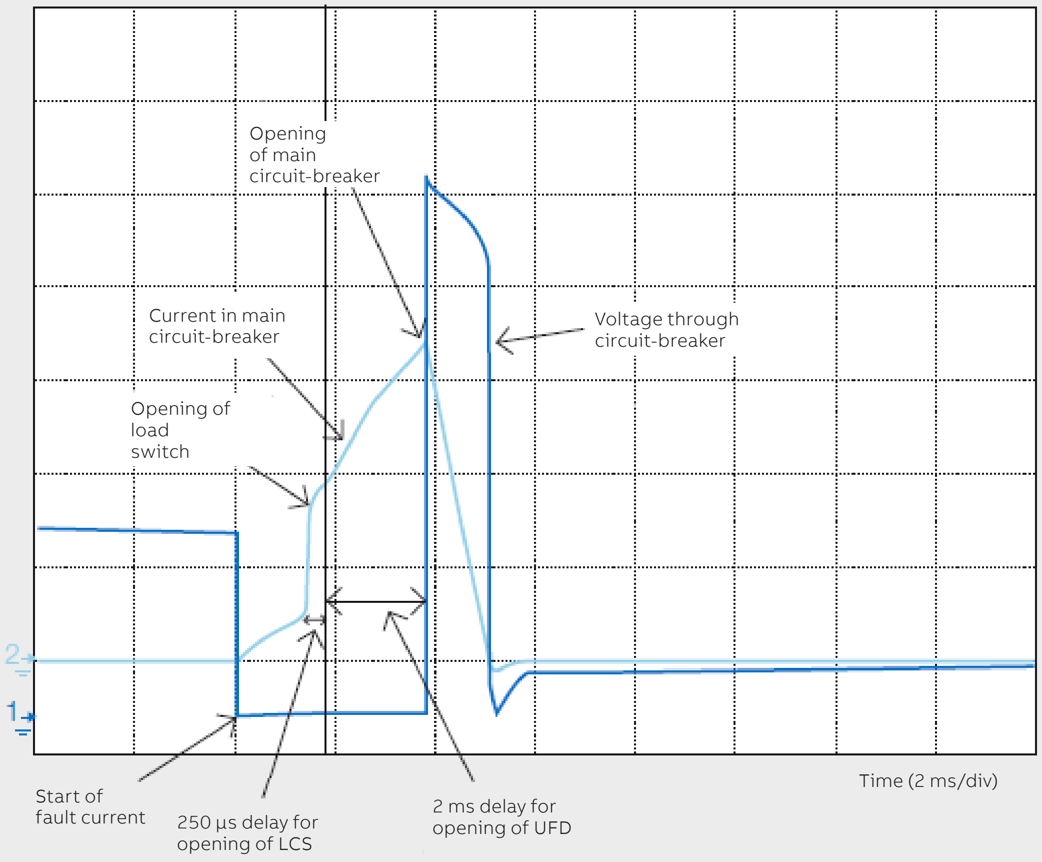

Figure 73: oscillogram of a break at 9 kA DC

4.2.3 Future developments

Developments are possible in all the technologies involved in the production of DC circuit-breakers. Further improvements can be made to the arc chutes and opening speeds of mechanical circuit-breakers so as to increase the DC breaking capacities.

Attempts to improve circuit-breakers with passive and active oscillating circuits will concentrate on optimizing the components of the resonant circuit, such as inductances, capacitors and varistors. The attainable goal is to improve the dimensions, break time and costs.
Further research into the characteristics of the arc and its shape, both in SF6 and vacuum, can lead to benefits such as increased oscillation and breaking capacity.

When it comes to hybrid circuit-breakers, the high-speed breaker is certainly one of the critical issues to be faced in relation to further developments.

Research into the most suitable semiconductors is an on-going commitment for both these and for purely static circuit-breakers. For example, ABB is now researching into the use of BiGT (Bi-mode Insulated Gate Transistors), which include the functionality of back-biased diodes in the IGBTs, something that could double the breaking capacity and raise it to 16 kA DC.
Other SiC-based (Silicon Carbide) or GaN-based (Gallium Nitride) semiconductors are now being produced.
Here again, purpose-made dynamic models will have to be developed for these high voltage and current circuit-breakers so as to simulate their behavior when breaking.

Lastly, further developments could be obtained from the application of technologies able to limit the fault currents.

5. Regulatory framework

The absence of specific legislation governing direct current is one of the critical factors for the development of new switchgear and controlgear, especially in MV and HV.

To date, the majority of the regulations governing direct current concern medium voltage railway systems, installations on ships and low voltage systems.

Table 4 contains a list of the standards in force at the present time that deal specifically or at least partly with direct current:

Body	Standard	Description	Purpose
IEC	IEC 60850	Railway applications – Supply voltages of traction systems	- Specifies the main characteristics of the supply voltages of traction systems, as fixed installations for traction, including the auxiliary devices supplied by the contact line and the rolling stock, to use in: • railway lines; • guided public transport systems such as trams, light rail, elevated and underground railways and trolley systems; • systems for transporting materials via rail, e.g. coal or iron ore. - This standard is also applicable to low speed MagLev trains or transport systems driven by linear motors.
IEC	IEC 60077-3	Railway applications – Electric equipment for rolling stock – Part 3: Electrotechnical components – Rules for D.C. circuit-breakers	- In addition to the general requirements of IEC 60077-2, this provides regulations for circuit-breakers, the main contacts of which must be connected to the DC supply and/or to the auxiliary circuits. - In accordance with IEC 60850, the rated voltage of these circuits does not exceed 3000 V DC.
IEC	IEC 61992-1	Railway applications - Fixed installations - DC switchgear - Part 1: General	- The IEC 61992 series specifies the requirements for the DC of electrical switchgear and controlgear and is intended for use in fixed electrical systems with rated voltage up to 3000 V DC, which supply power to guided public transport vehicles, i.e. railway vehicles, vehicles for tramways, subways and trolleybuses. The general requirements are given in Part 1.
IEC	IEC 61992-3	Railway applications - Fixed installations - DC switchgear - Part 3: Indoor D.C. disconnectors, switch-disconnectors and earthing switches	- Contains the requirements for the DC of disconnectors, switch-disconnectors and earthing switches used in the fixed indoor installations of traction systems.
IEC	IEC 61660-1	Short-circuit currents in D.C. auxiliary installations in power plants and substations - Part 1: Calculation of short-circuit currents	- Describes the method for calculating DC short-circuit currents in the auxiliary systems of power stations and substations, which can be equipped with the following apparatuses, acting as sources of short-circuit current: • three-phase AC rectifiers with bridge connection for 50 Hz; • fixed lead batteries; • voltage balancing capacitors; • direct current motors with independent energizing - Provides a generally applicable calculation method, which produces sufficiently accurate conservative results.
IEC	IEC 61975	High-voltage direct current (HVDC) installations - System tests	- The tests described in this standard are based on bidirectional and two-pole high-voltage direct current installations (HVDC) comprising a transmission terminal and a receiving terminal, each connected to an AC system. - This standard only serves as a guide for the system tests of high-voltage direct current installations (HVDC). - The standard provides potential users with information about how to plan the putting into service activities.
IEC	IEC TS 61936-2	Power installations exceeding 1 kV A.C. and 1.5 kV D.C. - Part 2: D.C.	- Provides, in an appropriate form, common regulations governing the design and installation of electrical systems in installations with rated voltage values over 1.5 kV DC for the purpose of ensuring safety and correct operation for the required use.

IEC	IEC 60204-11	Safety of machinery - Electrical equipment of machines - Part 11: Requirements for HV equipment for voltages above 1 000 V A.C. or 1 500 V D.C. and not exceeding 36 kV	- Applies to the equipment and to the electrical and electronic systems of machines, including groups of machines that operate together in a coordinated way, excluding the aspects of higher-level systems (i.e. communication between systems).
IEC	IEC 60364-1	Low-voltage electrical installations – Part 1: Fundamental principles, assessment of general characteristics, definitions	- Defines the regulations for designing, assembling and checking electrical installations. These regulations intend to protect the safety of persons, animals and property against the dangers and damage that could occur during the proper use of electrical installations and to ensure that such installations function correctly. - IEC 60364-1 covers circuits supplied at rated voltage up to 1000 V AC or 1500 V DC.
IEC	IEC 60947-2	Low-voltage switchgear and controlgear – Part 2: Circuit-breakers	- Applies to circuit-breakers with main contacts designed to be connected to circuits with rated voltage up to 1000 V AC or 1500 V DC. Also contains the additional requirements for integrally fused circuit-breakers.
IEC	SG4	LVDC distribution system up to 1500V	This deals with: - Coordinating the standardization of different areas, e.g. data centers, office blocks and shopping centers, etc. - Energy efficiency, EMC, reduction of natural resources - 100% DC installations or with AC and DC hybrid architecture - life-cycle of protection and earthing equipment
IEEE	PC37.20.10/ D6	Approved Draft Standard for Definitions for AC (52 kV and Below) and DC (3.2 kV and Below) Switchgear Assemblies	- The terms and definitions in the standard are intended to encompass products within the scope of AC (38 kV and below for air-insulated equipment, 52 kV and below for gas-insulated equipment) and DC (3.2 kV and below) power switchgear assemblies, including components for switching, interrupting, metering, protection and regulating purposes as used primarily in connection with generation, transmission, distribution and conversion of electric power.
IEEE	DC@Home	DC powered house	- Standards and roadmaps for LVDC Microgrid application in residential houses. - The aim is to: • Create un business case for DC by determining the effective losses and their value • Identify the research work required to advance the state-of-the-art • Establish the preliminary recommendations concerning the way in which DC would be delivered to houses - Written for the AC system, but some of its contents could be used as a reference for establishing the standards governing DC systems.
IEEE	IEEE 1547	Requirements for interconnecting distributed resources with electric power systems	Contains: - operation in the islanded mode and with connection to the grid - normal and non-normal operation - requirements and practices for distributed sources
IEEE	IEEE 1709	Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power System on Ships	Contains guidelines to specify, procure, design, manufacture and develop manuals, safety procedures, practices and procedures for effective maintenance of medium voltage direct current (MVDC) electrical power systems. - Recommendations are made for analytical methods, preferred interconnection interfaces and performance characteristics for reliable integration of MVDC electrical components into ship MVDC electrical power systems. - This guide contains indications about planning and designing DC connections which terminate at points of connection to AC systems, with low short-circuit values in the direct current supply.
IEEE	IEEE 1204	Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities	- This guide is limited to the aspects of interactions between AC and DC systems that result from the fact that the AC system is "weak" compared to the power of the DC link (i.e. the AC system appears as a high impedance at the AC / DC interface bus). - The guide contains two parts: Part I, AC / DC Interaction Phenomena, classifies the strength of the AC / DC system, provides information about interactions between AC and DC systems and their mitigation on economics and overall system performance, and discusses the studies that need to be performed.
IEEE	IEEE Std 1653.6	Trial-Use Recommended Practice for Grounding of DC Equipment Enclosures in Traction Power Distribution Facilities	Deals with the earthing of DC equipment enclosures installed in DC traction power distribution facilities as well as the related insulation treatments required for sound and resistant earthing methods. - Guidelines are also given for the material, installation and testing of insulation used in DC traction facilities and further recommended criteria for acceptability are provided. Even though related, the earthing system is not covered in this document.

IEEE	IEEE 1227	Guide for the Measurement of DC Electric-Field Strength and Ion Related Quantities	- The purpose of this document is to provide guidance for the measurement of electric field strength, ion-current density, conductivity, monopolar space-charge density and net-space charge density in the vicinity of high voltage DC (HVDC) power lines in converter substations and in apparatus designed to simulate the HV/DC power line environment. - The document defines the terms used, describes the interrelationship between electrical parameters, describes operating principles of measuring instruments, suggests methods of calibration where applicable, describes measurement procedures and identifies significant sources of measurement error.
IEEE	IEEE 946	Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Systems	Revision of IEEE Std. 946-1992. Guidance for the design of DC auxiliary systems for nuclear and non-nuclear power generating stations is provided by this recommended practice. - The components of the DC auxiliary power system addressed by this recommended practice include lead-acid storage batteries, static battery chargers and distribution equipment. - Guidance for selecting the quantity and types of equipment, the equipment ratings, interconnections, instrumentation, control and protection is also provided.
IEEE	C37.14	Standard for DC (3200 V and below) Power Circuit Breakers Used in Enclosures	- This standard covers enclosed low-voltage DC power circuit-breakers of the stationary or draw-out type of one- or two-pole construction with one or more rated maximum voltages of 300 V, 325 V, 600 V, 800 V, 1000 V, 1200 V, 1600 V or 3200 V for applications in DC systems having rated voltages of 250 V, 275 V, 500 V, 750 V, 850 V, 1000 V, 1500 V or 3000 V; high-speed circuit-breakers and for rectifiers; manually or power-operated; with or without electromechanical or electronic trip devices. - It also deals with service conditions, ratings, functional components, temperature limitations and classification of insulating materials, dielectric withstand voltage requirements, test procedures and applications.
IEEE	C37.16	Standard for Preferred Ratings, Related Requirements, and Application Recommendations for Low-Voltage AC (635 V and below) and DC (3200 V and below) Power Circuit Breakers	- This standard defines the preferred ratings for low-voltage AC (635 V and below) power circuit-breakers, general purpose DC (325 V and below) power circuit-breakers, heavy-duty low-voltage DC (3200 V and below) power circuit-breakers and fused (integrally or non-integrally) low voltage AC (600 V and below) power circuit-breakers.
NEC	Article 393, 625, 690, 692	Legal codes including introduction of DC technology	- Presents DC technology
MIL	STD-1399	Electrical interface characteristics for shipboard equipment	- Includes sections that define the requirements of DC equipment for shipboard supply systems
ETSI	EN 300 132-3-1	Power supply interface at the input to data/telecom equipment	- About data / telecommunications equipment for voltage levels up to 400 V - Considers the voltage level during normal operation and the requirements for various types of non-normal operation, the fault current limits, earthing and EMC.
Emerge Alliance	DC Microgrid	Standards for occupied spaces and data center	- Describes the architecture and control systems recommended in DC Microgrids.
REbus	Open standard	Open standard for DC electricity distribution in homes, commercial buildings, campuses, and other settings	- Defines DC distribution for operation parallel to the existing AC system - Coordinates renewable energy generation on site, including solar modules and small wind turbines - Defines a common 380 V DC bus with acceptable variation depending on the state of power supply, load and storage.
The Green Grid	White papers, calculation tools and industry glossary	Set of definitions and tools to determine and compare operational efficiency in data centers.	- The Green Grid association is a nonprofit industry consortium of end users, policy makers, information and telecommunications technology (ICT) providers, facility architects and utility companies. Its purpose is to improve the efficiency of IT resources, including use of DC distribution.

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Table 4: list of standards governing direct current

6. Future prospects

An increase in the use and installation of DC microgrids with low or medium voltage distribution can be forecast for the future. MVDC distribution will certainly become a valid option, especially in industry, where it can be used to supply processes that already use DC for production purposes. This will necessarily lead to new types of architecture and protection systems being researched, for the purpose of guaranteeing flexibility and continuity of service.
When it comes to the power distribution managed by Public Utility Companies at voltage below 36 kV, use of direct current must compete with the tried-and-tested, mature and economical AC system.
Nevertheless, the constant increase in loads and power generation that use DC natively plus the attention of public opinion and the authorities towards reducing consumption, will certainly cast doubts on the convenience of continuing to perform double DC-AC-DC conversions and encourage the assessment of new solutions by distributing DC directly to the users.
The DC distribution market is by no means united at the present time. This is demonstrated by the various consortia established to promote the use of direct current in office blocks and shopping centers, in homes, data centers or for telecommunications. For the moment, the Public Utility Companies have mainly invested in HVDC transmission lines for interconnecting microgrids or remote parts of the power grid, profiting from advantages deriving from the use of direct current or because they are forced to by the need to decouple grids at different frequencies (e.g. Japan).

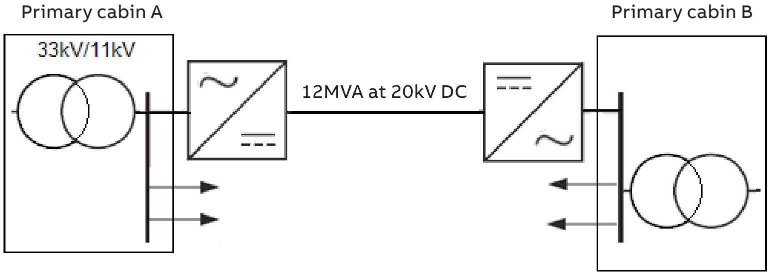

Figure 74: connection between two primary MVDC substations

Other possible uses of DC can contribute towards increasing the potential DC distribution market, thereby making dedicated investments profitable for the Public Utility Companies. For example, and as partly described in the sections on applications, some of these uses are:

- Long-distance suburban lines to connect rural areas or remote locations where power is generated from renewable sources
- Urban cable circuits
- To increase the capacity of the lines without increasing the fault level
- Decoupling areas affected by disturbance or with different power factors
- Decoupling areas with critical voltage variations or power flows
- Benefits that Public Utility Companies could obtain from improved use of the existing structures, allowing them to postpone or even avoid making important investments, e.g. for doubling the capacity in certain areas. Since use of static inverters intrinsically allows fault current to be limited, the protection systems on the AC side could remain unchanged. Benefits deriving from decoupling critical areas could also improve flexibility, and lead to economic benefits.

If a 20kV DC connection line with two back-to-back converters is added to the example in figure 74, the transmission capacity between two 11 kV AC substations could be increased by dynamically managing the active power flow, balancing the loads and power factors.

This solution would prevent the protections of the two primary substations from having to be modified and would keep the disturbances and power factors confined within their respective areas.
Development of real MVDC distribution grids, which is already an effective requirement in electric ships, poses the problem of protecting the grids themselves. A task that cannot be entrusted to the fault current limitation provided by static converters since this would not guarantee continuity of service for users not affected by the fault. Medium voltage direct current circuit-breakers must be used to eliminate the faulty circuits, as is already in use in AC systems.
In conclusion, the circuit-breaker continues to be the fundamental factor for future MVDC distribution grid design.

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