

1

Introduction

This introduction explains the background reasons why the gas-insulated transmission line (GIL) will play an increasing role in the future of electric power supply and why this book is being written today.

1.1 Changing Electric Power Supply

The power transmission systems of today will see basic changes in the near future. The impact of global warming affects the structure of electric power generation. Regenerative energy sources will be used to a much greater extent than today. Onshore and offshore wind, solar thermal, photovoltaic, biomass, hydropower, geothermal and sea-based power generation using wave, tidal or under-sea current power generation are all regenerative resources to generate electric power.

The sources of regenerative electric power will enter the electric power market as large-scale generators or as distributed small-sized power installations. Large-scale electric power and generation locations are usually far away from the load centres, and need to be connected through the electric power grid [1].

To handle these new electric power resources, intelligent power flow control is needed – a so-called “smart grid”. Smart energy consumption based on prices traded on the electricity market will require electric energy transmission from generator to consumer. Changing power flows caused by the availability of regenerative power sources such as wind, sun, waves, tides and all the other fluctuating regenerative energy sources will need power flow control and long-distance power transmission. Energy storage will play a much more important role if fluctuating regenerative energy is to be used efficiently. Storing regenerative energy when it is available and using the stored energy when regenerative energy generation is not available will balance the power supply. This is a requirement for the effective future use of regenerative energy.

There are several methods to store electric energy. The most common method is to pump water to a higher level when energy is available for a low price and use the pumped water to generate electric energy when the price is high. Today, such pumped storage power plants are designed to deliver peak energy for some hours a day. Large storage devices can deliver 1000 MVA for some hours, then they become empty and need water to be pumped again.

Large storage devices can only be built in remote and sparsely populated areas, which are far away from the consumers of electricity. In Europe, for example, this would mean Norway. The available space in the Alps or Pyrenees is very limited. And lower-altitude storage does not provide the required energy capacity. Remote storage will require additional transmission lines to connect the storage with consumers.

Compressed air in large volumes in mines or underground caverns offers another possibility to store large amounts of electrical energy. Here, air will be pumped into the mine or cavern in cases when a surplus of regenerative energy is available. When no regenerative energy is available the compressed air is released through turbines to generate electricity. Today, prototype mines are under investigation in Europe and the USA, and the expectation is that this could be a relatively low-cost storage solution close to consumers where mines or caverns are available [223].

A very large storage capacity is available when the surplus of wind and solar power is used to produce hydrogen (H_2) by the electrolytic process, and store it at high pressure (about 30 MPa) in a large storage cavern in the salt layer – about 4000 to 5000 m under ground. This technology is being used today to store large quantities of natural gas. These storage capacities can be used to bridge long periods of no wind, which can occur for example in January in the North Sea for several days. The stored hydrogen can then be used with burned-in turbines to generate electricity.

Cooling or heating of residential houses or commercial cool houses is another possibility to store electric energy. Cooling or heating can be adapted to the availability of regenerative energy. When regenerative energy is available, the heating or cooling is done up to higher or down to lower temperatures. The building stores the energy using the time constant of the building. This can be part of the pricing of energy, and heating or cooling of buildings plays a role in balancing energy consumption.

Storage of regenerative energy in batteries of electric vehicles is another opportunity to balance the electric power supply. Electric vehicles stand still most of the time (80–90% of a car's lifetime is spent stationary). The batteries of electric vehicles are widely distributed and offer a large storage capacity for electric energy. Connected to the network, electric vehicles can be controlled by a smart grid to take electric energy from the network or to deliver electric energy to the network. Batteries can be used in short cycles to change from charging to delivering and can make an important contribution to a stable electric power supply based on regenerative energy sources, which are fluctuating.

Storage of surplus regenerative energy will be a key feature in the regenerative electricity market. In times when more wind or sunshine is available then the electricity market can take electric energy. This will be stored and sold later at higher prices when the electricity market requires more energy.

Small and large-scale storage facilities will be used and needed. A typical distributed small-scale storage facility is formed by the e-car batteries, as explained above. In terms of time, it covers short and mid-term sequences of minutes and hours. If the sequence of non- or low levels of regenerative energy generation reaches days or even weeks, large-scale storage facilities are needed.

Large-scale regenerating power installations installed in the near future will be far away from power consumption in metropolitan areas. Regenerative generation in offshore wind farms or desert-located solar power generation will be located in areas with low power consumption. Metropolitan areas and large cities cover only a very small part on the earth, and their density

and electric power consumption is growing. Large power storage facilities will only be available far away from consumers [2, 3].

This will lead to long-distance, high-power transmission lines to connect power generation with power consumption. To balance regenerative energy sources it will be necessary to interconnect large distances, for example from the North Sea and Baltic Sea to the French or Spanish Atlantic coast; or the North East of the USA with the South East to take advantage of different wind situations in distant areas [4].

The power transmission system of today does not offer an optimized long-distance, high-power transmission network. Only relatively weak interconnections between regions are installed to cover emergency situations after the loss of large power generation (e.g., 1500 MVA) in one region when power from another region is needed.

Today, thermal power plants are located close to consumers and provide the required electric energy in a region. The future of regenerative energy generation is different, and requires an overlay network for continuous transmission of high power over longer distances, a so-called “super grid”, or overlay network. The super grid will bring energy from the power generation locations to the consumers of electric power in the load centres and to the locations where electric power can be stored (e.g., hydropower pumping storage).

For other reasons, such high-power, long-distance electric power transmission has been and will be installed in China and India. Both emerging countries are building up their electric power supply by using large resources of hydropower when building dams, for example the Three Gorges in China or Tehri in India. Electric power of several gigawatts is transmitted over very long distances of 1000 km or more into the metropolitan areas of, for example, Shanghai or Mumbai.

Experience with state-of-the-art high-voltage transmission technology in China and India shows that long distances are operated over with high reliability and high efficiency – power transmission lines of ultra high voltage (UHV) for AC systems with 1000 kV AC and DC systems using ± 800 kV DC. Since the year 2010 in China, ± 800 kV DC is also in operation to connect large power generation stations to metropolitan areas. These long transmission lines are built as overhead lines using very high towers (typical 70–80 m) and also large bundles of conductor wires (8–10 wires in a bundle of about 500 mm to 800 mm diameter). Such large overhead lines may not be possible everywhere, and underground solutions for at least sections of the transmission line may be needed. The need for high-power transmission and the possibility of combining overhead transmission lines with underground solutions make the GIL a good candidate for an overall solution, or at least part of the solution [217].

Today, large-scale wind farms onland and offshore are in planning or under construction. Large-scale photovoltaic generation or solar thermal generation is in planning and the first pilot projects are proving feasible. While wind is mostly best at sea and sun shines best in deserts, long-distance transmission is needed to compensate for fluctuation and to bring the regenerative energy to the consumers.

When overhead lines cannot be built, then the GIL offers an alternative solution to going underground with the same amount of energy as the overhead line can transmit (e.g., at 400 kV the transmitted power is 2000 MVA).

More than 40 years’ experience of first-generation gas-insulated technology is an excellent basis for using GIL as a high-power transmission system underground. The gas-insulated technology was introduced to substations in the late 1960s and is widely used today with high reliability. The introduction of second-generation GIL in 2001 using N_2/SF_6 gas mixtures

and pipeline laying methods to reduce costs makes the GIL a long-distance, high-power underground transmission system with high reliability and availability for the future [168].

1.2 Advantages of GIL

GIL offers several advantages for high capacity power transmission, as listed below [9, 10].

Low Transmission Losses Resistive losses are low because of the large cross-section of the conductor and enclosure pipes. Typical GIL resistances are 6–8 mΩ/km depending on the outer diameter (500 mm or 600 mm) and the wall thickness of the enclosure and conductor pipe (6 mm to 15 mm). The transmission losses are related to the square of the transmitted current as $P_v = I^2 \cdot R$ (I = current, R = resistance). When the current rating is high – as it is for GIL (e.g., 3000 A) – then the effect of low transmission losses is high. The losses through the insulating gas are negligibly small.

Low Capacitive Load Electric phase-angle compensation is only needed at very long lengths, because the capacity of the GIL is low, typically 55 μF/km. Therefore, no or low compensation coils are needed under most network conditions for transmission lengths of about 100 km. This also reduces the thermal operation losses.

Power Rating Like an Overhead Line The GIL is the ideal alternative or supplement to overhead lines. The high power transmission capability of the GIL (up to 3000 MVA per system at 550 kV rated voltage) allows it to go directly underground in series with an overhead line without power reduction. The GIL also allows the use of protection and control systems in the same way as with overhead lines. No differential protection is needed for failure location when a GIL is combined with overhead lines. The GIL has a low capacitance and, therefore, the inrush current is low.

High Level of Personnel Safety The outer enclosure pipe is solid grounded and no access to high-voltage parts is possible (gas-tight enclosure). Personnel safety is also guaranteed in case the GIL has to carry a short-circuit current (50, 63 or 80 kA up to 1 or 3 s). Even in case of internal failure and an arc between the enclosure and conductor pipes, tests have shown that no external impact occurs on the surroundings.

High Reliability The only purpose of the GIL is electric power transmission. No internal switching or breaking capability is needed. Based on this, the GIL can be seen as a passive high-voltage gas-insulated system with no active moving parts (e.g., switches). Today, more than 300 km of single-phase lengths has been in operation world-wide for more than 35 years. So far, no major failure (arc fault in the system) has been reported. This makes the GIL the most reliable power transmission system known.

No Electric Ageing Gas insulations do not age. The best example is an overhead line with ambient air as insulating gas. The electric field strength of the insulators and the maximum temperature of the GIL are too low to start the process of electrical or thermal ageing. This has been proven using long-term measurements in independent laboratories and also by extensive

experience with the equipment in the network. The first GIL installations have been in operation since 1974, and the results are reported by the CIGRE [71, 224].

Operation Like an Overhead Line Overhead lines in the transmission network are operated with the so-called autoreclosure function. This means that in case of a ground fault detected on the line, the circuit breaker will automatically break the lines, wait some seconds (depending on the network condition) and then switch on again. In most cases the reason for the fault current detection will be gone and the transmission line will go back to normal operation (for example, if a tree branch gets too close to an overhead line, the branch will be burned away or if a lightning strike causes the fault current, that will also be gone after some seconds).

Electromagnetic Fields To protect the public and the operational personnel international regulations require electromagnetic field limitations. These values vary across regions and countries depending on laws and regional regulations. A trend can be seen worldwide that limiting values are getting lower and the restrictions harder. In densely populated areas and cities these electromagnetic field requirements are defining the allowed design of transmission lines.

The GIL is operated as a solid grounded installation and the inductive loop is closed through the ground connection. The coupling factor is about 95%. This means that the superposition of the two reverse currents reduces the outside magnetic field by 95%, and only 5% of the magnetic field of the conductor current is effective outside the GIL.

Because of the induction law, the current in the conductor will induce a current in the enclosure of the same size and with 180° phase shift. The superposition of both electromagnetic fields is close to zero. In case of limitation of the magnetic field in the surroundings, this solid grounded GIL can fulfil even very low magnetic field requirements. With a current rating of 3000 A, within a few metres' distance a magnetic field strength of 1 µT can be reached (as required in some countries).

The advantage of a low magnetic field is important when residential areas are close to the transmission line – for airports with their sensitive instruments, hospitals with their sensitive imaging systems, or all kinds of sensitive electronic equipment in private or business use.

In Italy, electromagnetic field requirements for new installations go down to magnetic flux values of only 0.2 µT. When residential areas are involved, the GIL can reach such low values over a distance of a few metres.

No Thermal Ageing The GIL is designed for maximum operational temperatures given by the surrounding conditions – maximum 60 or 70°C touching temperature in a tunnel, or 40 or 50°C when directly buried. The different temperature values depend on individual countries and their applied standards and regulations.

In all cases the maximum allowed temperature of the conductor of 100 to 120°C is not reached by far. Therefore, no practical ageing of the system can be expected under these operating conditions.

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