Close and Return

Direct Current Gas-Insulated Transmission Lines: Development and testing of the ±550 kV DC GIL

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ABSTRACT

This technical paper give information about the status of DC gas-insulated transmission lines (DC GIL). With technical information related to the historical steps of development it will be shown that DC gas-insulated systems are in investigation since more than 40 years and deliver operational experiences since more than 20 years. The focus of the development today is driven by the need of high power underground transmission lines in cases when overhead lines cannot be build. Future applications as directly buried installation or laid in a tunnel are explained. Such underground transmission lines may be combined with existing infrastructure like highways, railroads, pipe line routes, rivers or canals. The main challenges for developing DC gas-insulated systems test programs for dielectric tests as well as thermo-electric testing with insulation system tests are shown. These tests vary strongly from the AC tests of gas-insulated systems. The prototype installation test is a long term test program to prove the correct installation and safe operation simulating the live time of the DC GIL will be explained in the text.

KEYWORDS

DC gas-insulated systems, GIL, Gas-insulated Transmission Lines, DC GIL, HVDC Transmission

INTRODUCTION

The invention of gas-insulated high voltage technology goes back to the special electric properties of SF_6. This gas was invented in the first place for the chemical and metallurgical industry as an oxidation stopper. Because of the weight 5 times heavier than air, SF_6 can be flooded on top of a chemical fluid to disclose oxygen and with this oxidization. But a second feature of SF_6 is the high electric insulation capability which has been used by MIT - Massachusetts Institute of Technology in the 1960s to design the first SF_6 insulated high voltage system with DC direct voltages [1]. The idea to use DC was logic, because with DC the power losses in a high power transmission system are lower than with AC. No reactive power losses with DC and the possibility of long transmission lines offered new technical solutions with DC GIL. Plans have been created to connect large metropolitan areas in the USA like New York with Chicago using DC GIL. This first approach was not successful because of non-understood effects of DC voltage like trapped charges or surface effects and charges. The development moved to AC and then was successful with gas-insulated substations and transmission lines until today. This gas-insulated technology proved to be very reliable. Once installed the mean time between failure of AC GIS and GIL which will cause a power transmission interruption is in the range of 1000 years. Long time experiences collected by CIGRÉ prove these very reliable values [2].

Today the basic knowledge of DC high voltage gas-insulated systems has been widely improved. Physical effects related to electric charges of the insulating gas, the insulators or any of the surfaces can be explained. The impact of temperature on the insulators is basically understood and proven by tests in the laboratory. For free moving particles in DC gas-insulated systems the physical behavior and movement differs fundamentally from the one in AC. Therefore new design of particle traps is required to capture and keep free moving particles safe. The effectiveness of the new particle trap design has been proven in laboratory tests using real size equipment. The principle requirements for type testing DC gas-insulated substations (DC GIS) and transmission lines (DC GIL) are in development in CIGRÉ JWG D1/B3.57: "Dielectric Testing of gas-insulated HVDC Systems". The principles are positive and negative test voltages, including electric charging times, thermal heat up to cover cold and warm condition. Positive and negative impulse voltages superimposed to DC voltage cover the transient overvoltage in service like lightning stroke or switching impulse voltage. The so called insulation system test represents a special test for the insulators with all relevant DC stresses. In addition the DC prototype installation test represents the prove of correct assembly processes for DC GIL and safe operation under high voltage and rated current condition to represent lifetime of the equipment.

First DC gas-insulated switchgear was installed in Japan in the 1990s [3] and is still in operation without any failure reported. These long-term DC experiences and the more than 40 years of excellent experiences with AC gas-insulted technologies in service are the basis for the DC GIS and DC GIL design of today.

The goal of the DC GIL development today is to create a high power underground transmission system for long distance applications and at acceptable costs. Initiated by the wish in Germany to underground three north – south links to connect the regenerative wind power generation in the north with the industrial concentration in the south. Acting as a high voltage overlay network, possibly ±500 kV, these transmission lines will be used to transfer large amounts of electric energy, controlled by DC converter stations to provide a stable network in central Europe. Because of the dense population in Germany and the high objection of the public the politicians decided with the "Renewable Energy Network Code" to underground the DC lines of a length of about 700 km for each link.

The technical requirements for such underground links are high current ratings and low losses. The DC GIL can transmit up to 5000 A as a continuous DC current when directly buried in the ground and laid in thermal stable bedding materials. This has been test successful in a long term test at the Siemens test laboratory in Berlin. In combination with highly automated laying and jointing processes for the works on site and a localized installation structure similar to the pipe line laying processes the total project cost can be reduced to an economic level. At power transmission ratings of 5 GW per ±500 kV plus and minus pole new technical applications are getting possible. Using highway routings or other infrastructures like train routes, pipe line routes, existing overhead lines or shipping canals new applications can be realized even in dense populated areas.

FUTURE APPLICATIONS

Due to the continuing urbanization and concentration of the industrial centers in developing countries the needs for the transmission of higher amounts of power for long distances are growing worldwide. Further example is the merging of the huge offshore wind parks and need for transmission of generated power to urban and industrial areas. German's “Energiewende” for instance requires the construction of three north – south DC links of 700 km length each. Each of new transmission lines connecting the offshore wind parks in the Northern of the country to the main power consumption centers in the South.

Along with traditional alternating current technology, direct current transmission lines are getting more importance for transmission of electrical power for long distances from generating to consumption point.

Due to the lack of space and increasing environmental awareness of the population as well as of politics, no new overhead transmission lines for the entire required long lengths can be constructed, at least in the western countries. Two principal technologies exist for underground power transmission, cable and GIL. Based on the project requirements, e.g. transmission capacity, routing flexibility, environmental specification, maintenance and life cycle management, the optimal technology shall be defined.

The laying methods for cable and GIL are different. Cable sections shall be as long as possible to avoid the high number of connecting joints. The typical cable section lengths amount to several 100 m and are limited by the transport weights (size of conductor cross sections) and transport dimensions (width and weight).

The principle of the GIL laying is based on the module sections of 10 to 15 m, which can be easily transported and welded on site using automated welding methods. To increase the laying speed of long GIL installations can be performed at several sites in parallel along the route.

Figure 1 shows the principle of a direct buried GIL parallel to a highway, exemplarily for one bipole system.

The use of existing infrastructure routings is a primary choice for new underground electric transmission lines. With existing railroad routes the underground transmission line may be laid in parallel. Also pipeline routes or shipping routes in rivers or canals can be used in combination with DC GIL. The German expert society of ETG for power engineering has investigated this topic in detail and published in a report [8].

As a conclusion the best chances of a realization is the combination of DC GIL and highways as shown in **Figure 1**, directly buried or in as in **Figure 2** in a tunnel. This technical solution is now investigated on an example

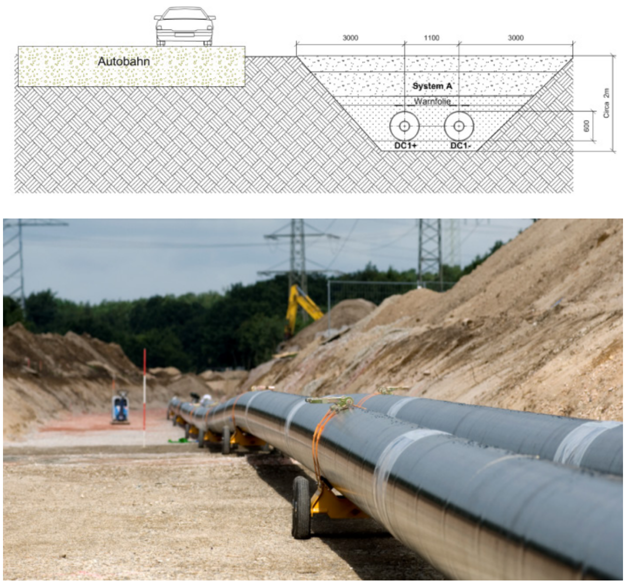

Fig. 1: Principle of a direct buried GIL during installation in the trench

of 600 km length in parallel to a German highway. The publication is expected in early 2018.

Figure 2 shows the option of a tunnel GIL laying, in this case exemplarily for two bipole systems. Tunnels may lay fully underground, half buried or above ground depending on the requirement along the route. The tunnel offers also personal access during operation or in case of a repair.

The GIL offers an underground transmission solution without any fire load; this is a major advantage for tunnel installations and for the use of existing infrastructure (e.g. railroad tunnels).

DEVELOPMENT OF DC GIL

Main challenges

At first view, the DC GIL technology and design is analogous to the AC GIL design used for decades in numerous projects. The main components are aluminium

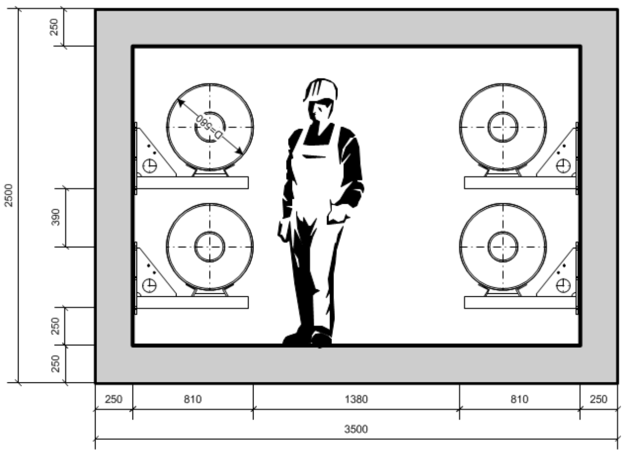

Fig. 2: Principle of a tunnel GIL – in this example with two DC GIL bipole systems

tubes and conductor, epoxy resin insulators and insulation gas mixture. But, on the basics of physical phenomena with DC current and voltage stress, several effects have to be considered for the development of DC GIL:

- Dielectrics: Transition from the capacitive AC field distribution (controlled by ε_r) to the resistive DC field distribution (controlled by κ); surface and volume charge accumulation; temperature-gradient dependent electric field distribution
- Particle behaviour: Different behaviour for positive and negative polarity: at positive polarity the particles show much stronger movements between conductor and enclosure than at AC. At negative polarity the particles hold up at the conductors' surface [4].

As a consequence, the adaption of the insulators (geometry and material) and the development of DC particle traps suitable for both polarities are the main challenges for the development of the DC GIL.

Modules of the DC GIL

Similar to the AC GIL technology, the DC GIL can be composed of different types of modules. The main is the straight module (**Figure 3**), which is joined by welding of the conductor and the casing tube. A support insulator is mostly used in this module. For mechanical fix points of the conductor or for the separation of gas compartments (e.g. every 500 m), a disk insulator is used in the straight module. The insulation gas is a mixture of N_2 and SF_6, which is a compromise between a compact design of the DC GIL and environmental aspects. By the jointing via welding with a 100 % ultra-sonic test of every welding seam, the system should be considered as almost completely gas-tight for lifetime.

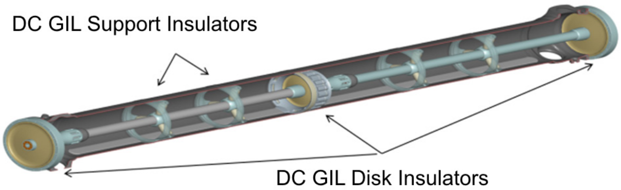

Fig. 3: Principle, modular design of the DC GIL

By bending of the straight module tubes, curves with a minimum radius of $r = 600$ m (depending of laying type) can be realized. For tight bends, angle modules with 45° or 90° are available (**Figure 4** and **Figure 5**).

For the installation of longer distances with DC GIL, several optimizations of the installation procedure (welding, laying) are developed; these solutions are described in detail in [5].

TESTING OF DC GIL

For the testing of gas-insulated HVDC equipment like DC GIL, no test standards are available up to now. However, the CIGRÉ Joint Working D1/B3.57 is preparing test procedures taking into account all the relevant physical phenomena.

Compared to AC systems, the tests are more complex and significantly more time-consuming.

Testing of the insulation system

One of the main developments for gas-insulated HVDC systems (DC GIS and DC GIL) are suitable insulators. With respect to the different physical phenomena, a test procedure for five insulators of each type should be carried out. The focus of this test is the reproduction of all the different stresses which may be relevant for real service conditions:

- DC voltage pre-charging in order to get the resistive field distribution with the accumulation of surface charges on the interface insulator-gas and bulk charges in the insulators
- Heating of the inner conductor to the operational temperature at nominal current
- Superposition of the pre-charged test assembly (by DC voltage) with and without temperature gradient along the insulators with impulse voltages (LI/SI)

Depending of the material parameters of the insulators and the ambient temperature, the pre-charging time has to be determined. Typically, the pre-charging time can be some days to weeks. For the heating of the conductor during the tests, inductive heating with AC current may be one possible solution.

Figure 4 shows the test setup with 10 specimens for the DC GIL with inductive heating. The superposition of DC voltage with impulse voltage is realized by a spark gap.

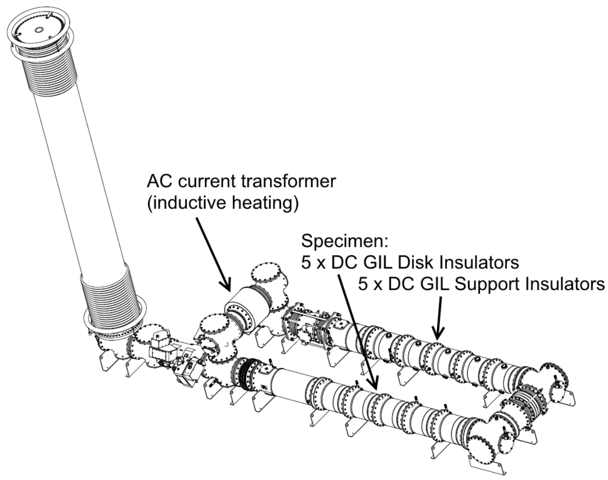

Fig. 4: Test setup for the insulation system test of the DC GIL insulators with temperature gradient

Dielectric testing of the modules

Due to the fact that all types of DC GIL insulators have been tested in the insulator test mentioned above, dielectric tests under cold conditions (without temperature gradient) are satisfactory to prove the dielectric strength of all the different modules.

Analogous to the insulator test, the modules have to be tested with DC voltage with both polarities and with the superposition of DC voltage and impulse voltages in the pre-charged condition as well.

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Figure 5 shows the DC GIL test setup consisting of all the different modules. The test setup is located at the Siemens high voltage laboratory in Berlin, Germany. The test voltages and test procedures are orientated on the CIGRE D1.B3.57 working group recommendations which will be published in 2018.

Test voltages (±500 kV network nominal voltage):

- DC voltage: 1,5·$U_{m,cov}$ = 1,5·±550 kV = ±825 kV
- Lightning Impulse Withstand Voltage: ±1550 kV
- Switching Impulse Withstand Voltage: ±1175 kV
- Superposition of DC with LI/SI (homo- and heteropolar superposition):

  ±550 kV ∓1550 kV LI / ±550 kV ∓1175 kV SI

Long term prototype installation test

Considering the test for HVDC cable systems, a test procedure is established according to Cigré TB 496 [6] covering ageing effects of polymeric insulation. This test procedure has been adapted to the needs of gas-insulated transmission lines for AC applications AC GIL in CIGRÉ TB 218 [9]. For gas-insulated HVDC systems, the necessity of long term tests is under discussion: Even though the cast resin insulators shows no ageing phenomena, the arguments for a long term test are the lack of experience with the new HVDC technology under real service conditions [7].

Therefore, all different major modules of the gas-insulated systems should be tested, being installed by using the same installation procedure as for future customer projects. Tests on GIL systems will require a certain length giving the chance to neglect cooling effects at the test set-up's boundaries and to test the thermo-mechanical behaviour adequately. [7]

The long term prototype installation test is based on type test components which have been tested according to the requirements of the insulation system test. In the long term prototype installation test, the DC GIL with all available modules will be tested under realistic operational conditions to prove the correctness of the assembly and on site high voltage tests for an estimated lifetime of 50 years.

This prototype installation test will be executed at a test field for long duration test. The DC GIL test loop will have a total length of about 300 m.

SUMMARY & OUTLOOK

The development of DC GIL is following the market needs of high power underground transmission lines. This requirement is coming from the restructuring of the transmission network under the conditions renewable energy generation which is usually far away from the load centers. This is a work-wide effect to the transmission network, but in countries like dense populated Germany the available and acceptable space for new overhead lines is limited and the German government decided by law to underground new high power transmission lines. DC GIL can offer up to 5 GW of transmitted power for one ±500 kV system (two GIL conductor poles).

The realization of long length installations required automated jointing and welding process to increase the laying speed. To reach this, new welding process based on friction stir welding (FSW) and automated DC GIL module handling [5] will reach speed improvements which results in reduced total costs. At the end, the DC GIL can deliver an economic solution for high power underground electric power transmission.

The first installation may be realized in a few years and in a European conjunction an overlay network at highest DC voltages levels may be installed to provide power exchange over long distances. This is a basic requirement for stable power supply network in Europe for a renewable energy generation world.

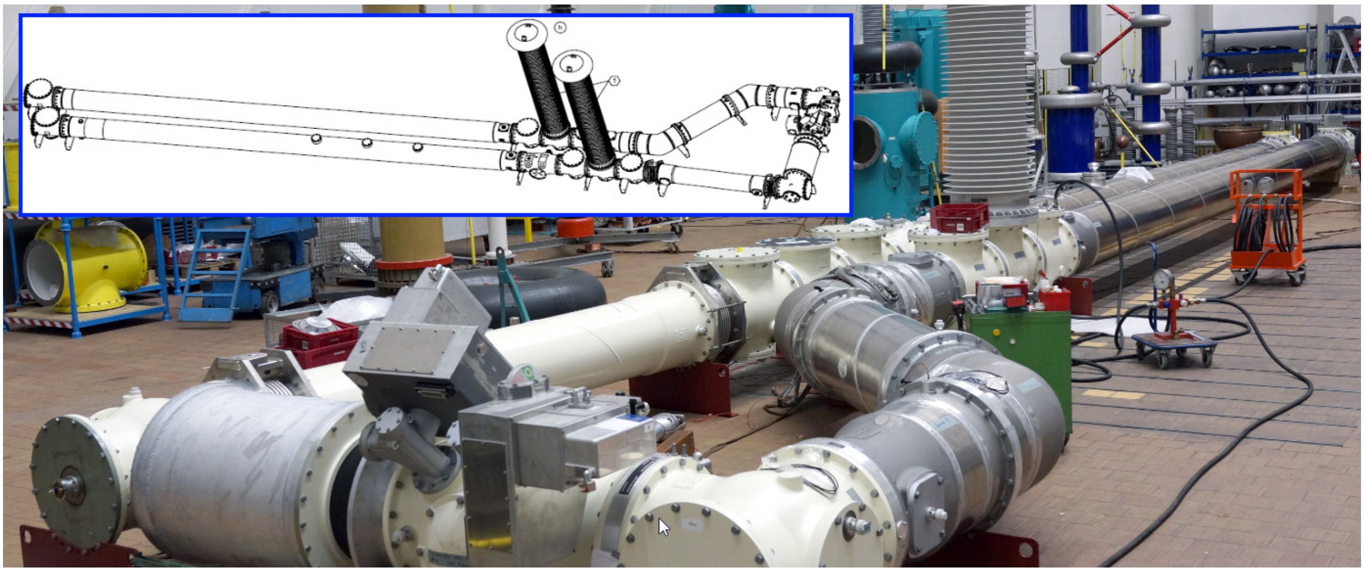

Fig. 5: Photo of the 22m dielectric test assembly in the high voltage test laboratory with two standard DC GIL modules, 45° and 90° angle modules, compensation modules and disconnector/earthing module

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GLOSSARY

ε_r: permittivity, here permittivity of the epoxy resin insulator

κ: conductivity; here surface and volume conductivity of the epxy resin insulator

$U_{m,cov}$: Maximum continuous operating DC voltage (e.g. ±550 kV for the ±500 kV network nominal voltage)

DC GIL: Direct Current Gas-insulated Transmission Line
DC GIS: Direct Current Gas-insulated Substation
GIL: Gas-insulated Transmission Line
HVDC: High Voltage Direct Current
LIWV: Lightning Impulse Withstand Voltage
MIT: Massachusetts Institute of Technology
SF_6: Sulphur-Hexafluoride
SIWV: Switching Impulse Withstand Voltage
HVDC: High Voltage Direct Current