21, rue d'Artois, F-75008 PARIS
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2016 CIGRE-IEC Colloquium
May 9-11, 2016
Montréal, QC, Canada

High Power AC and DC Underground Transmission Lines

H. KOCH, D. IMAMOVIC
Siemens AG
Germany

SUMMARY

The latest developments of AC and DC underground transmission lines are presented in this paper. The focus on the AC underground transmission line is on new applications and methods of laying, while the DC version is a new technology now under development in Siemens. Both technologies are seen as an additional solution to solve high power transmission when underground laying is necessary.
The applications of AC gas-insulated transmission lines (GIL) started in 1974 and showed a strong increase in transmission length over the last years. The concentration of energy transmission with rated currents of up to 5000 A at a rated voltage of 550 kV made the AC GIL a best fitting solution to solve underground transmission tasks. World-wide underground bulk power transmission is getting more and more important due to restricted available space and higher concentration of electric load, mainly close to metropoles and large cities. Also the power generation is going to higher values as hydro power project in China shows. The increase of required electric power at concentrated locations requires power transmission solutions which allow maximum use of the available space. GIL is the technical solution which offers both requirements: highest power transmission and smallest space requirement. An outlook is given about the improvements of the laying process by using the concept of a mobile factory and new welding methods.
The DC technology of Compact Transmission Line (DC CTL) is coming into focus with new HVDC transmission line in Germany with the requirement to underground high power transmission of up to 5000 A and +/- 500 kV at sections of the overall 2000 km long new installations of DC lines. The technical performance of this new technology is presented. Based on more than 40 years of experience at AC voltage with more than 200 km phase length installed and operated world-wide with highest reliability, the DC gas-insulated technology follows the same principle and uses the same material type for insulators, aluminium enclosures and conductors. The DC Compact Switchgear which includes disconnector and ground switch function is already type tested and ready to deliver for voltages of +/-320 kV. The +/-500 kV equipment is now under development and first results will be presented in this paper.
One main question of gas-insulated DC voltage technology is the way how to test. Voltage level and voltage forms need to be defined for DC voltages. In CIGRE working group D1/B3.57 is in charge of defining these test criteria. The experience made so far by test carried out at the Siemens laboratory in Berlin shows that a combination of DC voltage, switching impulse and lightning impulse voltages need to be applied. In this paper test results will be presented and an outlook on how to apply in field test will be given.

hermann.koch@siemens.com, denis.imamovic@siemens.com

The future application of GIL in AC and DC is related with the main benefits of high power transmission capability, a low capacitance for AC, lower resistive losses compared, low electromagnetic fields, no ageing phenomena of the insulating system and a maintenance free design.

KEYWORDS

Underground Transmission Line – Compact Transmission Line (CTL) - Gas Insulated Line (GIL) – AC Line – DC Line – DC Compact Switchgear (DC CS) – DC Design - Mobile Factory – DC Testing – Tunnel Laid – Direct Buried

1. Introduction

The requirement of high power underground transmission is world-wide increasing. The increase of load in cities and dense populated areas is asking for more transmission capacity and the limited availability of space gives strong restrictions on the right of way.

In addition, public and political opinion is often in strong opposition to overhead lines and the will is there to spend more money for underground solutions. In some cases the value of land of wide corridors for power transmission can compensate the additional cost partial or even overcompensate, depending on the local cost per square meter. And an overhead line corridor of a 500 kV line is in the range of 100 m compared to 10 m of a compact power transmission line like GIL or DC CTL.
The technology of gas insulated high voltage equipment was invented in the 1960s and first installations are in service for high voltage switchgear since 1968 and for 420 kV gas-insulated transmission lines (GIL) since 1974 with very high reliability.
he principle of this technology is simple: an aluminium conductor, inside an aluminium enclosure, kept in the centre by cast resin insulators and filled with insulating gas. At the bottom a particle trap will take care about any dust particle inside and capture particles in the low electric field are below the particle trap, see Fig. 1.

The first generation of GIL is using pure SF_6 for insulation and still is using pure SF_6 when applied in substation together with gas-insulated switchgear, usually called bus-duct.
The GIL shown in Fig. 1 is a second generation of transmission technology using SF_6/N_2 gas mixture with an 80 % content of N_2. This was possible at the same dimensioning of 500 mm diameter for voltage ratings up to 550 kV maximum voltage of the equipment because the GIL does not provide any switching function, only insulation [2].

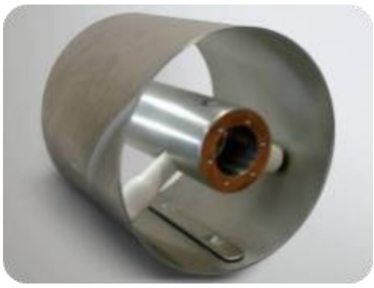

Fig. 1: Principle of gas-insulated technology
Aluminum conductor and enclosure, cast resin insulator and particle trap, filled with insulating gas

A second new design feature of this second generation GIL is the simplified, modular structure which reduces the complexity of used parts to assemble the GIL for a transmission line. Only four modules are necessary: straight, angle, disconnecting and compensation modules. The straight module is the core element to cover the distance. Assembled from 12 - 15 m long segments which are jointed by automated orbital welding including a 100 % ultrasonic weld test a length of about 200 - 300 m form a fix point unit depending on how large the maximum temperature change will be. Depending on the maximum temperature change the maximum thermal expansion is fixed. The partition insulators act as fix point between enclosure and conductor pipes and the post type insulators are sliding with the thermal expansion.

Gas compartments are formed in lengths up to 1.5 km. This limitation of gas compartments is optimized to the laying process when vacuum must be reached down to 1 mbar low pressure before the system can be filled with the N_2/SF_6 gas mixture. In case of a repair the gas compartment limitation allows maximum repair time when laid in a tunnel of about one week and when directly buried of about two weeks before the system can be re-energized.

In Fig. 2 the principle elements of a fix point section is shown. The fix point is provided by the partition insulator shown at the right. Thermal expansion of the conductor is moving to the left where post type insulators (white) can slide in the inside of the enclosure. The conductor movement will be compensated by a contact system of the other and before the next fix point partition insulator. The distance between may be 200 m to 300 m depending on the maximum temperature change between cold (system off) and full power [2].

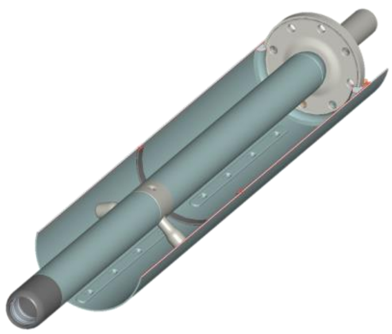

Fig. 2: Simplified GIL module
Conductor with contact system and enclosure, post type and partition insulator

There are two principles for underground transmission lines: laid in a tunnel or directly buried.
Tunnel laid GIL is using small concrete trenches with concrete covers or micro tunnels with diameters of 1 - 2 m or accessible tunnels of 3 - 4 m diameter which is shown in Fig. 3. The tunnel has in principle the advantage of accessibility to the system. The best accessibility is provided in an accessible tunnel as shown in Fig. 3. With a diameter of 3 m in this tunnel two three phase AC systems up to 550 kV can be installed providing electric power transmission of up to 4000 MVA in one tunnel depending on the local laying conditions.

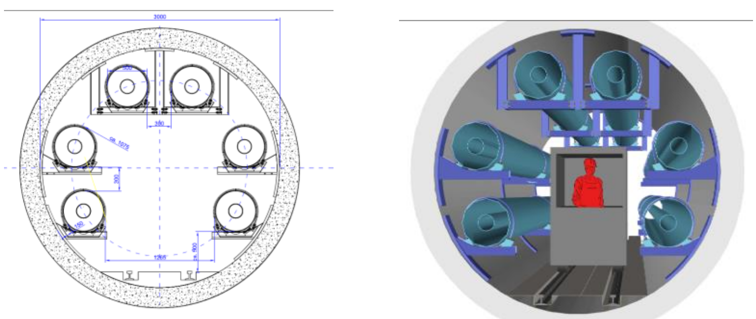

Fig 3: Bored tunnel for two three phase AC systems up to 550 kV and 4000 MVA power transmission

These tunnels are equipped with transportation and inspection systems using video inspection during operation to avoid people in the tunnel.

The bored tunnel in Fig. 3 is using tunnel boring machines which are used for traffic tunnels of long length, e. g. the 50 km long St. Gotthard Tunnel in Switzerland. This tunnel boring technology has been developed over the last years and costs have been brought down to provide economical solutions today. Depending on the geological condition tunnel cost levels of 3 - 4 Mio EUR per kilometre can be reached.
An alternative method of laying long tunnels is given by the use of concrete tunnel elements as shown in the graphic in Fig. 4. Here the same high power transmission can be provided at smallest space as in the bored tunnel.

Fig. 4: Squared tunnel for two three phase AC systems up to 550 kV and 4000 MVA power transmission

The squared tunnel segments are produced in parallel to the laying of the transmission line with parallel production. This allows high laying speed and the application also for long distance applications of several tens of kilometres.
The directly buried GIL may be laid directly into the soil using a passive corrosion protection of a PE layer or it may use PE pipes with GIL inserted as shown in Fig. 5. In both cases a corridor of about 10 m is sufficient to transmit a bulk power of 4000 MVA at 550 kV.

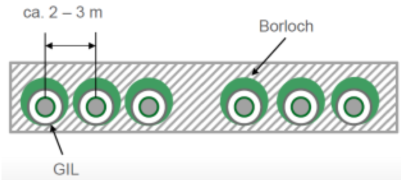

Fig. 5: Directly buried GIL for two three phase AC system up to 550 kV and 4000 MVA power transmission

DC Transmission

The presented DC gas-insulated technology has a long history. Since the invention of SF_6 for the use of high voltage insulation the idea was born to take the advantage of two concentric aluminium pipes for high power underground transmission. Since the 1970s and 1980s in USA, Japan and Europe developments for up to 500 kV DC have been carried out, followed by first installations and tests [1].
The first application has been made in Japan at the Kii Chanel project for a compact switchgear design including disconnector and earth switch connected to a sea cable between the island of Honshu and Shikoku. The design of tis installation is made for 500 kV with a relative large diameter of the enclosure of one meter. The transmission cable is operating at 250 kV and in service until today.
New requirements of today e.g. with the ‘Energiewende’ in Germany high power underground transmission lines are needed to comply with public opposition on overhead lines which give a strong visual impact mainly in dense populated areas. Directly buried and tunnel laid solutions are needed

together with the compact design of HV DC switchgear to disconnect and earth. DC circuit breakers are not needed because of the use of full bridge converter stations.

2. AC Underground Applications

Palexpo

The use of gas-insulated technology for long distance applications started with the second generation of GIL in 2001 at the Palexpo in Switzerland at the Geneva Airport. The GIL replaces a length of about 400 m of an existing 300 kV overhead line. The rated current of 2000 A has the second requirement of less than 1 µT of magnetic flux density at the ground floor of the exhibition hall right above the tunnel with the GIL. Only GIL could meet this requirement in less than 5 m distance.

Table 1: Technical Data Tunnel Laid
Palexpo, Switzerland, 2001

Rated voltage	300 kV
Rated current	2000 A
Rated magnetic field	1 µT (in 5 m distance)
Short circuit current	50 kA, 1 s
Insulating gas mixture	80 % N_2 and 20 % SF_6
Tunnel length	420 m
In operation	since 2001

The two three phase AC GIL systems have been installed within 3 months, completely gas tight welded and following in elastic bending the S-shape of the tunnel the minimum bending radius is about 700 m as can be seen in Fig. 6.

Fig. 6: Palexpo tunnel with two three phase AC systems, 300 kV, 2000 A

Kelsterbach

Ten years later the longest GIL project of 420 kV voltage rating has been executed at the Kelsterbach project at the Frankfurt International Airport with a system length of about one kilometre in 2011. Here the extension of the airport required to underground an existing overhead transmission line. Two three phase AC systems can transmit 4000 MVA. The laying was done in an open trench and the single phase insulated GIL was pulled from the assembly and welding tent phase by phase into the trench. The total installation process was concluded in less than six months. The open trench before backfill is shown in Fig. 7.

Fig. 7: Kelsterbach two three phase AC systems directly buried of 420 kV and 2750 A

Table 2: Technical Data Direct Buried
Kelsterbach, Germany, 2011

Rated voltage	420 kV
Rated current	2750 A
Lightning impulse withstand voltage	1425 kV
Short circuit current	63 kA, 1 s
Insulating gas mixture	80 % N_2 and 20 % SF_6
Buried system length	1 km double system
In operation	since 2011

Langwied

The Paulaner Brewery in Munich is one of the deliverer of beer for the "Oktoberfest". According to the city rules only beer can be sold at the "Oktoberfest" which is brewed within the city limits of Munich.
So the new planned brewery needed a location there which was found under a 420 kV overhead line. Because of the strict requirements of the brew master of below 1 µT the GIL was the only technology that could guarantee this at a maximum current rating of 3150 A.
The existing overhead line is an important North-South link and is foreseen to be extended up to four three-phase AC systems for 2300 MVA each.
The tunnel is prepared for four GIL systems and has a length of 500 m including a minimum bending radius of 400 m to follow foundation requirements of the brewery building above, see Fig. 8.

Fig. 8: Langwied tunnel with two three phase AC systems, 420 kV, 2300 A
Space for two additional systems

Table 3: Technical Data Tunnel Laid
Langwied, Munich, Germany, 2014

Rated voltage	420 kV
Rated current	2300 A
Lightning impulse withstand voltage	1425 kV
Short circuit current	63 kA, 3 s
Insulating gas mixture	80 % N_2 and 20 % SF_6
Tunnel length	500 m
In operation	since 2014

3. AC Technology Improvements

Now the third generation of compact transmission lines based on gas-insulated technology is in development. Two main goals are behind the third generation design: improved assembly and laying of the pipe segments and robust and reliable joint technology using new welding processes.
These improvements will further reduce the time for installing GIL which impact almost 50 % of the total cost. The mobile factory combines the automated assembly of GIL segments with the welding process. The mobile factory as shown in Fig. 9 is equipped with a pipe magazine where on-site prepared pipe segments are stored and made ready for the welding. There are two welding work places which work alternatively to generate a continuous production of GIL segments to be pulled into the open trench or tunnel section.
Beside the jointing technology the mobile factory also is equipped with ultrasonic quality control of the welds to provide that only failure free welds are getting laid.

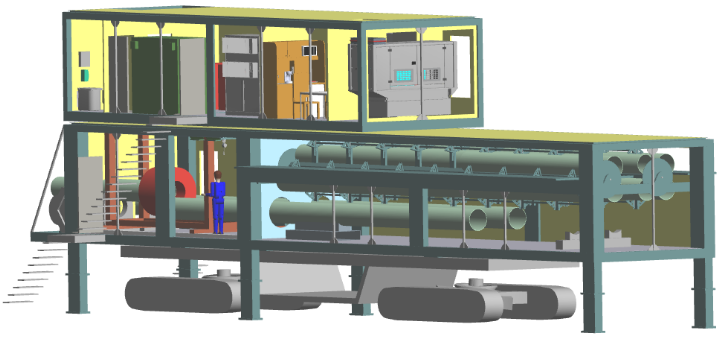

Fig. 9: Mobile factory for on-site assembly and laying

A new jointing technology based on friction steer welding has the advantage that the joint of two pipes can be made in only one orbital process, see Fig. 10. Compared to arc welding where 5 to 10 welds are required to conclude the joint, the friction steer welding is a much faster process. From one hour connecting time the process goes down to about 10 minutes. This reduced jointing time multiplies with the number of welds (about 300 welds per kilometre) and the reduction of laying time and with this reduction of cost.

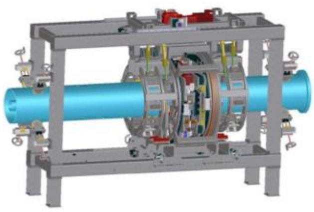

Fig. 10: New jointing technology based on friction steer welding

4. DC Transmission Technology

The same advantages of high power transmission and high reliability as given for AC GIL can be reached for DC, too. The experience is going back to the 1970s, as explained in the introduction, with some systems installed. The requirement of DC transmission is coming now with the increased use of high voltage DC transmission on shore, also in dense populated areas like Germany. The German Energiewende forwards a regenerative energy generation and supply with required sections of underground DC transmission in the next years.

With the shutdown of German nuclear power plants in 2022 the first DC lines are needed in 2019.
The compact design and high transmission capability make the DC compact transmission line (DC CTL) a good option.
In Fig. 11 the graphic shows the space of a 5 GW power transmission line using two gas-insulated pipes with 5000 A current rating at 500 kV DC. Less than 8 m space are required.

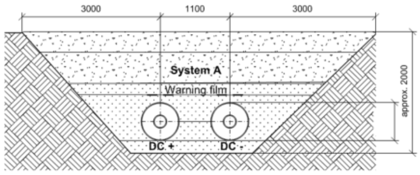

Fig. 11: Space required for 5 GW power transmission at 500 kV DC

The same space saving effect is given by using DC Compact Switchgear (DC CS), see Fig. 12. The photo shows the space saving of the DC CS compared to the AIS solution for disconnector, earth switch, overvoltage surge arrestors, current and voltage sensors [3].

Fig. 12: Space saving at the converter station with DC Compact Switchgear (DC CS)

Physical Principles of DC Gas-insulated Systems

Several effects compete in a gas-insulated DC system which impacts the dielectric performance of the system. The electric field distribution is changing with time right after the high voltage is applied. After the capacity of the transmission line is loaded by the capacitive charging current of the applied voltage the electric field changes to a resistive field distribution. The resistive field distribution shows a strong temperature dependency. The DC field shows impact on electrical charges on top and inside the insulators. This may be long time process, depending on the type of insulating material. The electric conductivity in the gas and insulators also is contributing to the electric stability of the DC system. Simply said, higher conductivities reduce the charging capability by increasing the losses produced by a constant current flow. Charge carrier generation due to electric field emissions from the conductor or ionisation effects are two more effects to be considered for the proper design of insulators in DC CTL.

Thermal effects provide internal gas convection, thermal radiation and thermal conductivity which have an impact on the temperatures in the gas, the insulator, the conductor and the enclosure. To understand these physical dependencies is the first step for the design of a reliable DC gas-insulated system as presented in Fig. 13.

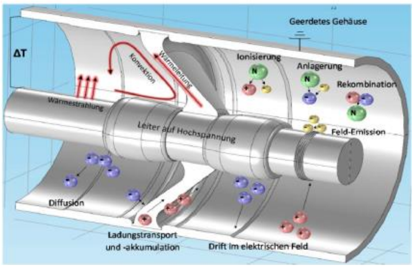

Fig. 13: Physical principles of DC gas-insulated systems

Insulators

Insulators under DC voltage change their electric field distribution from a capacitive mode to a resistive mode. In Fig. 14 the electric field calculation of a conical insulator is shown. The field strength distribution is shown in colours, blue for low fields and red for high fields. The AC high field areas are around the conductor surface and are low inside the insulator. This distribution does not change in time. The DC field distribution is changing in time depending on the current load of the system. When there is no temperature drop $\Delta T = 0$ between conductor and housing (zero current load) the resistive electric field concentrates inside the insulator near to the inner conductor. On the contrary, the insulator surface suffers to maximum electric field stress near the external housing when the conductor is warmer than the housing and temperature drop $\Delta T > 0$ (high current load).

The time constant for this change is depending on the insulator materials and the temperature. The design of the DC insulator and the right choice of material for the insulator must cover this effect.

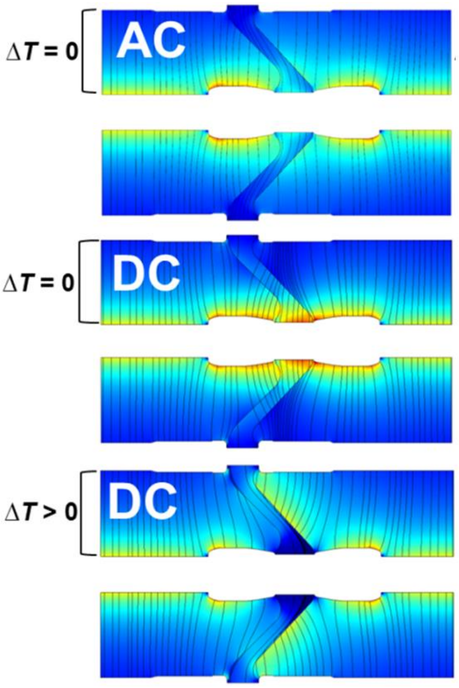

Fig. 14: AC and DC electric field distribution

Recommended Tests of DC Gas-insulated Systems

Testing of HVDC gas insulated systems is currently not standardized and in the focus of Cigré JWG D1/B3.57 “Testing of gas-insulated HVDC-systems”. According to recent discussions [4], dielectric tests will either be based on existing IEC standards for AC gas insulated systems or be addressed to specific effects occurring under DC voltage stress. Table 4 shows an overview of different tests and suggested voltage levels which were used for design, type and routine tests with the new DC insulation design.

Table 4: Recommended dielectric tests for DC gas insulated systems [9];
U_{rdc} – rated DC voltage (550 kV)

Type tests focus: gas insulation	DC voltage test Lightning impulse (LI) voltage test Switching impulse (SI) voltage test Superimposed voltage tests Polarity reversal test (optional)	1.5 x U_{rdc} for ≥1min IEC 60071-1/-5 (15 impulses) IEC 60071-1/-5 (15 impulses) 1.0 x U_{rdc} + LI / SI voltage (15 impulses) IEC 65700-19-03 (1.25 x U_{rdc})
focus: insulator-gas interface	Insulation system test: DC voltage and superimposed voltage tests at zero load and high load conditions	1.0 x U_{rdc} (90% charging time) U_{rdc} + LI / SI voltage (15 impulses)
Routine tests	Power-frequency voltage test, PD measurement	$\hat{U}_{pre-stress}$ = 1.5 x U_{rdc} (1 min) $\hat{U}_{pd-test}$ = 1.2 x U_{rdc} (≥ 1 min)
On-site tests	Power-frequency voltage test, PD measurement DC voltage test	$\hat{U}_{pre-stress}$ = 1.5 x 0.8 x U_{rdc} (1 min) $\hat{U}_{pd-test}$ = 1.2 x 0.8 x U_{rdc} (≥1 min) to be defined
Long term tests	Dielectric long term tests (in responsibility of manufacturer)	
Prototype tests	DC voltage and superimposed voltage tests (optional)	

For the verification of the DC insulators the following tests have been performed:

- Temperature rise tests under different laying arrangements (in a tunnel, directly buried)
- AC and DC voltage tests as shown in Table 4
- Lightning (LI) and switching (SI) impulse tests as shown in Table 4
- Superimposed voltage test after DC voltage pre-stress with "cold" conductor
- Insulation system tests as shown in Table 4

The tested insulators passed these tests and now prepared for long time testing and prequalification tests for the complete compact DC system (DC CTL) [4, 5, 6, 7, 8]. In addition, high-voltage, temperature rise and switching tests are performed with DCCS equipment for 500 kV DC, as well as special insulator tests.

5. Outlook

The need of powerful underground transmission systems as the compact AC transmission line (GIL) and DC transmission and switching technology (DC CTL and DC CS) based on gas-insulated technology for the future need in the power transmission network is seen today. Two main fields of applications are identified: replacement of existing overhead lines in dense populated areas where the value of the land is high and the need of new infrastructure and houses is high. This was the case in the examples given in chapter 2.

The second area for compact transmission lines are coming from the restructuring of the network towards a full regenerative power supply. This will require new transmission lines more as an overlay network to bring regenerative energies to the consumption areas. In dense populated regions also underground transmission in the range of 3 to 5 GW per transmission line will be needed.

These activities are very strong in Germany today and they are focused on DC to get better control on power flow in a fluctuating power generation scenario.

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