High-Capability Applications of Long Gas-Insulated Lines in Structures

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***Abstract*—This paper deals with the possibility of installing gas-insulated transmission lines (GILs) in dedicated or shared structures. The applications involve railway galleries (both in the proper galleries and in service or pilot tunnels), highway networks, and gas lines. The high GIL power capability together with very low power losses configures these applications as high transmission efficiency corridors. Some issues of this application will be shown in this paper (steady-state regime of the line, voltage drops, power losses, voltage unbalance factor, ampacity, electromagnetic field impact, and limit lengths). Moreover, this paper discusses the necessary studies to be carried out and the problems that have to be faced in order to develop this kind of application toward a feasible technical solution.**

***Index Terms*—Extremely high voltage (EHV) transmission lines, gas-insulated lines (GILs), multiconductor matrix algorithm, shared structures.**

I. Introduction

The authors, when facing the question of land constraints for electric infrastructures, have often begun with this outstanding passage taken from an EPRI book [1] that postulates the necessity to develop common corridors in order to satisfy the ever-growing exchanges between areas of large industrialized systems:

Common Corridors

For both ecological and economic reasons, future expansion of transmission systems especially near urban areas will have to consider sharing their rights of way with other land users. Independent use of land by single utilities can lead to inefficient use of natural resources. The development of new rights of way in future years will have to consider the location of suitable highway networks, gas lines, sewage systems, nearby utility transmission lines, telephone lines, underground transmission systems, and recreational areas. Such development will require a coordinated effort by government and industry. A current study in [2] outlines the approach that the electric utilities may follow to encourage full use of their transmission-line corridors.

This EPRI idea regarding the U.S., even with wide territory resources, is very well applicable to other places.

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This topic is so felt and argued in Europe that the International Council on Large Electric Systems (CIGRÉ) has established a Joint Working Group entitled "Application of long high capacity Gas Insulated Lines in structures" to study the feasibility and the characteristics of this technical solution. This JWG will last three years and will deliver a final brochure. A dismantled Joint Working Group 23/21/33.15 "Gas Insulated Transmission Lines (GIL)" delivered a brochure in February 2003 [3] but this is completely devoted to short length and directly buried GILs so that a prolongation of it in the direction of long length and installed in shared, dedicated structures, in tunnels or in galleries is greatly needed.

The question can be naturally applied to other underground technologies, most of all to XLPE cables. In fact, there is another CIGRÉ Working Group B1.08 entitled "Cable systems in multipurpose or shared structures" which is facing this different solution. The rationalization of fundamental services in the land, such as electricity and transport, both via rail and via highway, represents a higher degree of consciousness in conciliating environmental issues and technology. Of course, it is also a big technical challenge because it is not trivial that there is a full compatibility between possible different infrastructures. Moreover, there are a lot of projects of new galleries between neighboring countries (separated by mountain chains) and these possibilities represent absolutely unique opportunities for integrating (railway or highway) transport and energy transmission within the same corridor or within the same structure. This could strengthen the scarce transnational network between states whose electrical networks are responsible for giving high hindrances to an effective international electric market.

Sharing different nature structures and a power transmission line within the same corridor represents an optimization of service rights of way: conciliating technological society needs with a respect toward nature and territory seems to be the challenge of the 21st century.

II. Brief State of the Art: Actual Installations in Tunnels

The GIL world installations amount today roughly to 100 km and the longest line length is 3.3 km even if much longer runs are under study [4]. Only a few words about the technology [5], [6]: GILs are manufactured of factory-assembled elements. The elements (straight unit, angle unit up to 90°, axial compensator) may be $15/40$ m long. Under normal conditions of the landscape, no angle units are needed, because the elastic bending with a radius greater than 400 m is sufficient to follow the contour. Once the elements are placed, the phases are joined by means of plug-in contacts and the enclosures are joined by means of onsite welding. The enclosure welds are fundamental

Fig. 1. Wehr (Germany) tunnel with a double-circut GIL at 420 kV (in service since 1975, Siemens).

Fig. 2. A 300-kV double-circuit GIL in PALEXPO (Switzerland) Geneva Airport tunnel (in service since 2000, Siemens).

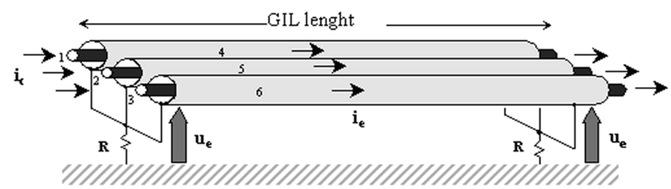

Fig. 3. Simplified model of a single-circuit GIL.

for the line reliability: for this aim, a special computer-controlled orbital welding machine is used; then, every welded part is checked with ultrasonic tests to reach 100% control quality. The high degree of reliability of these procedures comes from experience based on nuclear power plants. One of the first GIL applications is placed in a tunnel; it connects a pump storage power plant to the 420-kV network at Wehr (Black Forest in Southern Germany) (see Fig. 1). It has been commissioned in 1975. The route length is 0.7 km and the total length is $(6 \times 0.7) = 4.2$, km. Fig. 1 shows the double-circuit arrangement in the Wehr tunnel. This is an example of the first generation GIL with pure SF_6 as an insulating gas at 4 bar. In the last installations, the insulating gas is a SF_6/N_2 mixture (ratio of $10 \div 20\%$) at 7 bar.

Chubu Electric Power Co. Inc. has installed a 275-kV double-circuit GIL in a tunnel between the Shin–Nagoya Power Station and Tokai Substation [7]: the route length is 3.3 km. This is the longest actual GIL. In this situation, GIL was chosen to be a more economic alternative rather than XLPE cables, for which five circuits would have been required.

The city of Geneva decided to construct a new hall at Palexpo, near the Geneva–Cointrin international airport. The presence of an overhead line linking Verbois to Foretaille constituted a major obstacle in the way of the future exhibition hall. An underground tunnel over a length of approximately 450 m between two towers was the solution finally chosen [8]. The gas-insulated line solution was preferred rather than another technology, because of its low magnetic interference level, its high transmission capability, and reduced heating effect. This GIL replaces the overhead line between two pylons and it is composed of 162 pieces of straight GIL units, each 14 m long. In this tunnel application (see Fig. 2), the high transmission capability of GIL ensures that it will not be a bottleneck when inserted in the existing overhead line. Surge arresters are used at the GIL terminations. For monitoring and control of the GIL, there is first partial discharge (PD) ultra-high frequency (UHF) equipment to prevent insulation faults that can seriously damage the equipment, and secondary equipment is installed for the gas density measurement.

The state of the art indicates that all of the actual tunnel installations of GIL are short runs: this seems to be an intrinsic contradiction with the technical features of this electric line that is suitable for long lengths and bulk power transmission as it will be shown in the following.

III. GIL Features

A. Enclosure Currents Opposing Those of Phases: A Simplified But Noteworthy Matrix Procedure

The enclosures of the three phases of a GIL must be solidly bonded and grounded at both ends (solid-bonding) and at regular intervals along the line (multipoint grounding system): the strong mutual inductive phase-enclosure coupling together with the very low enclosure resistance, allow (in accordance with Lenz's law) the enclosure and phase current phasors to be nearly equal but 180° out of phase. In order to properly study the current distribution with a simple and evident procedure, let us consider the model of Fig. 3, where $\boldsymbol{i_c}$ (whose elements are i_1, i_2, i_3) is the conductor current vector, i_e (whose elements are i_4, i_5, i_6) is the enclosure current vector, and u_e and $\boldsymbol{u_e^*}$ are the enclosure voltage vectors at the sending end and at the receiving end of the line, respectively.

Considering only the longitudinal self and mutual impedances of the whole line, the foregoing vectors are related by the following equation:

$$\boldsymbol{u_e} = \boldsymbol{Z_{ec}} \boldsymbol{i_c} + \boldsymbol{Z_{ee}} \boldsymbol{i_e} + \boldsymbol{u_e^*} \tag{1}$$

with $\boldsymbol{Z_{ec}}$ and $\boldsymbol{Z_{ee}}$ calculated by means of Carson's theory.

TABLE I
ENCLOSURE CURRENTS FOR DIFFERENT GROUND RESISTIVITY VALUES

	ρ_g=100 [Ω·m]	ρ_g=1000 [Ω·m]	ρ_g=50000 [Ω·m]
i_c	i_e	i_e	i_e
1 ∠0°	0.992783 ∠-178.741°	0.992840 ∠-178.742°	0.992908 ∠-178.743°
1 ∠-120°	0.999463 ∠61.898°	0.999458 ∠61.899°	0.999453 ∠61.901°
1 ∠120°	1.006592 ∠-58.713°	1.006548 ∠-58.751°	1.006494 ∠-58.718°

By noting that $\boldsymbol{Z_{ec}}$ and $\boldsymbol{Z_{ee}}$ differ only in diagonal elements for enclosure resistances r_e

$$\boldsymbol{Z_{ee}} = \boldsymbol{Z_{ec}} + \begin{bmatrix} r_e & & \\ & r_e & \\ & & r_e \end{bmatrix} = \boldsymbol{Z_{ec}} + \boldsymbol{R_e}$$

and assuming that enclosures are perfectly bonded and grounded at the line ends, so that $\boldsymbol{u_e} = 0$ and $\boldsymbol{u_e^*} = 0$, (1) becomes

$$\boldsymbol{0} = \boldsymbol{Z_{ec} i_c} + (\boldsymbol{Z_{ec}} + \boldsymbol{R_e})\boldsymbol{i_e}$$

consequently

$$\boldsymbol{0} = \boldsymbol{I} \cdot \boldsymbol{i_c} + (\boldsymbol{I} + Z_{\mathrm{ec}}^{-1}\boldsymbol{R_e}) \cdot \boldsymbol{i_e}$$

where $\boldsymbol{I}$ is the 3×3 identity matrix. If enclosure resistances could be null, it would result

$$\boldsymbol{i_e} = -\boldsymbol{i_c}$$

(i.e., there would be a perfect opposition between conductor and enclosure currents) (hence, a perfectly zeroed external magnetic field). This phenomenon is not affected by the presence of earth resistances R but on the bonding between enclosures. The presence of earth resistances R becomes important when $\boldsymbol{i_c}$ holds a zero sequence (as in phase-enclosure short circuit). The multipoint earthing system allows to strongly reduce the touch voltages in case of the phase-to-enclosure short circuit. In regards to EHV cable lines in solid bonding, the currents induced in the shields are smaller than those in GIL enclosures due to the much higher shield resistances (e.g., 70 mΩ/km against 2.33 mΩ/km with subsequent very high power losses).

Considering typical enclosure resistance (i.e., 2.33 mΩ/km), three different values of ground resistivity ρ_g, and imposing positive-sequence currents in inner conductors, Table I reports the results. The high values of ρ_g chosen for the computations in Table I are well justified when considering a GIL installation in a mountain gallery with very high resistivity. The results of Table I show that the enclosure phasors change very slightly as a function of ground resistivity. This can be explained considering that the GIL flat arrangement is not a perfectly symmetric line so that there are very small zero-sequence currents flowing in the earth (they would be null in trefoil arrangement).

Moreover, it is worth nothing that the most important consequence of current opposition in GIL is the strong reduction of the magnetic field outside the line despite the low additional losses in enclosures. This simple but elegant matrix procedure takes into account the earth return currents but it is unable to consider the current density distribution in the enclosures. To this aim, the following section solves this issue.

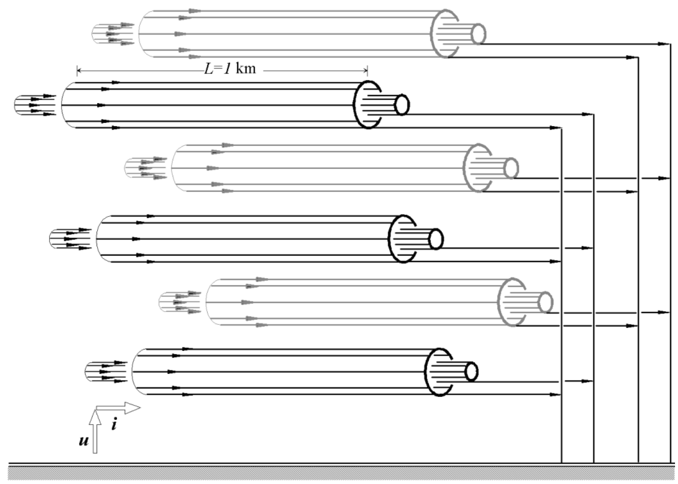

Fig. 4. Phase and enclosure bundled conductors for double-circuit GIL.

B. Proximity Effects in Gas-Insulated Lines

In the usual installations, the proximity effects are not so marked but their study becomes rather important when a close conductor arrangement must be considered (e.g., in a tunnel installation).

The authors have already developed a matrix integral algorithm to study the proximity effect of single-circuit GIL [9]: the generalization to the double-circuit GIL is detailed in [10].

The method is based on an extensive application of the matrix analysis of multiconductor systems: each phase and enclosure can be divided into a bundled equivalent conductor of m subconductors (see Fig. 4) whose self and mutual longitudinal impedances can be computed applying the Carson theory, which accounts for the earth return effects. So referring to subconductor voltage and current vectors $\boldsymbol{u}$ and $\boldsymbol{i}$ in Fig. 4, the following matrix equation can be written:

$$\boldsymbol{u} = \boldsymbol{Z}i$$

where $\boldsymbol{Z}(12 \times 12\ \mathrm{m})$ is the impedance matrix of the subconductor system. Moreover, the solution is achieved by considering a matrix relation, which takes into account the constraints at the sending end [9], [10].

A comparison with the finite-element (FE) method has been performed for both current distribution [9] and heat transfer [10], providing really good agreement.

In a simpler way, the proximity effects in GILs are always very slight because the external magnetic field (responsible for giving nonuniform current distribution) is always very low. These procedures allow calculating precisely the power losses taking into account the proximity effects and are therefore important for ampacity evaluation.

The closeness of each single-phase conduct plays an important role for room saving: the study of the proximity effects along with the necessity of avoiding strong nonuniformities in the current density distributions of the enclosures suggest not to decrease the distance between the enclosure (spacing from enclosure profile not from enclosure axis) limits below 0.3 m; however, this distance must hold also for orbital welding use.

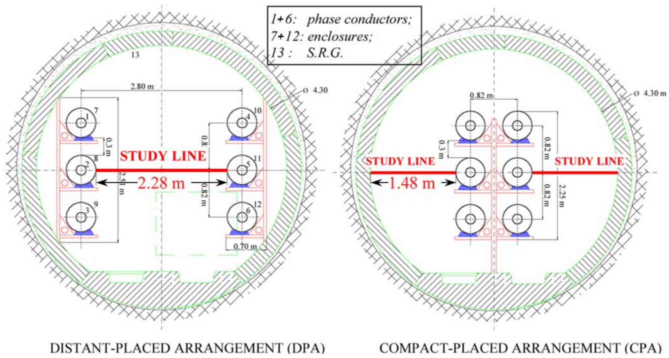

Fig. 5. Possible vertical arrangement installations of double-circuit GIL.

TABLE II
CONDUCTOR CURRENTS FOR DOUBLE-CIRCUIT GIL 400-kV
$|\underline{S}| = 3000$ MVA, GIL Length = 57 km

Receiving-end Currents [A]				
Phases			**Enclosures**	
R	**1**	$\|2164\| \angle{-14}°$	**7**	$\|2135.4\| \angle 168°$
S	**2**	$\|2164\| \angle{-134}°$	**8**	$\|2162.8\| \angle 48°$
T	**3**	$\|2164\| \angle 106°$	**9**	$\|2190.5\| \angle{-72}°$
T	**4**	$\|2164\| \angle 106°$	**10**	$\|2190.5\| \angle{-72}°$
S	**5**	$\|2164\| \angle{-134}°$	**11**	$\|2162.8\| \angle 48°$
R	**6**	$\|2164\| \angle{-14}°$	**12**	$\|2135.4\| \angle 168°$
Steel Reinforcement of the gallery (S.R.G.)			**13**	$\| \ 56.0\| \angle 143°$

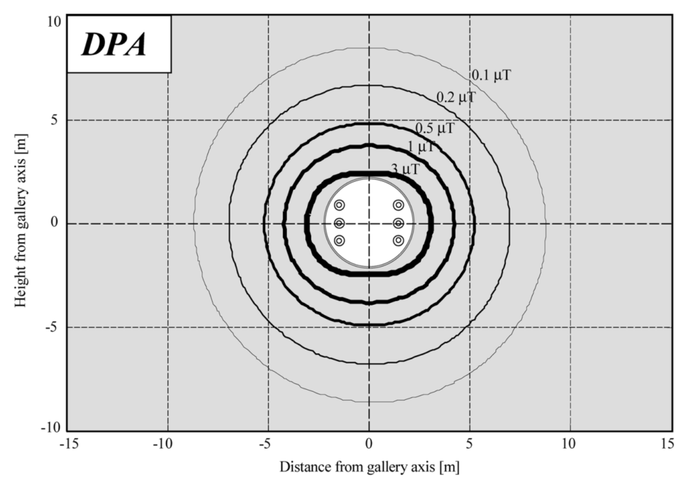

Fig. 6. Magnetic-field levels for DPA with current phasors in Table II.

C. Magnetic-Field Impact

In any GIL configuration, the magnetic-field impact is always extremely low: this depends upon the shielding effect due to the opposing currents flowing in the enclosures (almost equal in magnitude but opposing in angle to those of phases). This feature can play a key role when the installations require extremely low magnetic-field levels (i.e., in sensible zones, for EMC apparatus immunity, or in countries with highly restrictive magnetic field laws).

Let us consider a dedicated tunnel installation of a double-circuit GIL. In general, the vertical arrangement can be performed with the two circuits very close to each other (together on the left, right, or middle side of the pilot tunnel similar to the SHINMEIKA–TOKAI installation) or with the two circuits being diametrically opposite (see Fig. 5).

The former can be named compact-placed arrangement (CPA); on the contrary, the latter is "distant-placed arrangement" (DPA). It is worth remembering that the enclosures should be systematically bonded together and with the **S**teel **R**einforcement of the **G**allery (**S.R.G.**) at very short length intervals; this ensures equipotentiality between the tunnel wall and the GIL enclosures and constitutes very good distributed earthing.

By means of a matrix procedure [11] which considers the multiconductor system constituted by phases $1/6$, enclosures $7/12$, and the S.R.G. 13, it is possible to compute the current phasors in any conductors and in any cell along the line.

The procedure [11] neglects the proximity effects (which, as shown, are always very slight) but can calculate the induced current also in S.R.G.

Let us choose a loading of 3000 MVA $(\cos\varphi = 0.98)$ that corresponds to a receiving-end phase current equal to 2164 A. Therefore, Table II reports the system current phasors (for the phase sequence RST—TSR) computed by means of multiconductor procedures [11].

It is worth noting that the multiconductor procedure can exactly compute the enclosure and the S.R.G. current phasors: the enclosure currents phasors are almost equal to those of phase conductors but 180° out of phase.

All of the magnetic-field computations of this Section refer to the current phasors in Table II.

The value of 3 μT is reached at 3.13 m (see Fig. 6) while for the CPA of Fig. 7, the value of 3 μT is reached at 2.05 m. Fig. 8 shows the magnetic field inside the pilot tunnel along the study line of Fig. 5. The highest value is 50 μT (in close proximity of the enclosures). The shadowed zone in Fig. 8 (CPA) represents the nonviable area owing to the presence of the transmission line. It is worth noting that the magnetic field between the phase and enclosure is extremely high due to the lack of enclosure shielding effect. The generated magnetic fields are always very low: despite the other transmission technologies, this transmission system has the best "magnetic behavior" due to its optimum intrinsic shielding (the enclosures are low resistive and solid bonded).

D. Capability of Long AC EHV Gas-Insulated Lines

A coauthor has already developed some procedures to evaluate the operating capability of long ac EHV transmission XLPE cables [12]: this approach is worth applying to any distributed parameter transmission line (including overhead lines) and, hence, to GIL. Tables III and IV report the typical data and the parameters for the following analysis.

From Table IV, the low per-unit length capacitance c (54.5 nF/km) and the high ampacity should be noted, which is dependent upon the installation kind, but is always very high, namely from 2400 A to 3000 A. First, it is important to analyze the no-load regime, d_U and d_I are the no-load voltage and current

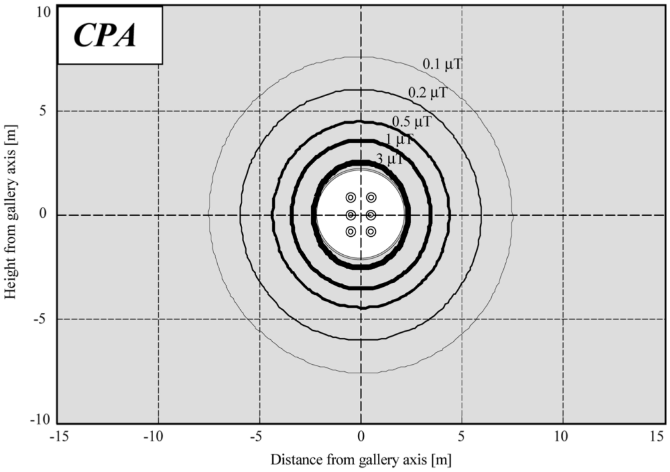

Fig. 7. Magnetic-field levels for CPA with current phasors in Table II.

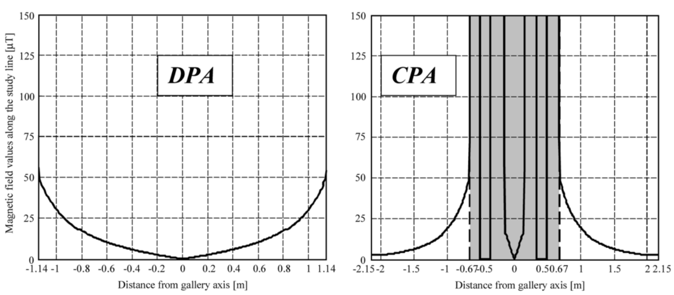

Fig. 8. Magnetic-field values inside the pilot tunnel along the study line.

TABLE III
TYPICAL DATA OF 400-kV GIL

Gas Insulated Line		
Cross sectional area of phase (Al IACS=61 %)	**mm²**	*5341*
Cross sectional area of enclosure (Al alloy IACS=52.57 %)	**mm²**	*16022*
Phase Outer Diameter	**mm**	*180*
Phase thickness	**mm**	*10*
Enclosure Inner Diameter	**mm**	*500*
Enclosure thickness	**mm**	*10*

limit lengths, respectively, which for the GIL of Table III are equal to

$$d_U = 308 \text{ km} \quad d_I = 542 \text{ km}.$$

It is worth noting that the limit d_U is more restrictive than d_I. However, these length limits are merely theoretical because the network nodes which the line is linked with have an infinite fault level. By means of a simplified but useful approach that allows considering the real fault level of the network source, the equivalent generator can be used (as seen at node S in a regime without the line): it is characterized by the no-load voltage (which is supposed to be $U_o^* = 230$ kV) and the short-circuit impedance (for simplicity is purely inductive jX_{Sc}); the no-load regime at R, derived from the insertion of GIL at S, is completely defined by

$$\underline{U}_{oS} = \frac{U_o^*}{jX_{Sc} - jX_C} \cdot (-jX_C) \qquad \underline{U}_{oR} = \frac{\underline{U}_{oS}}{A_{id}} \quad (2)$$

TABLE IV
PARAMETERS OF A 400-kV GIL

Gas Insulated Line			
Per unit length d.c. Resistance of phase at 60° C	r_{ph}	**mΩ/km**	*6.286*
Per unit length d.c. Resistance of enclosure at 50° C	r_{en}	**mΩ/km**	*2.330*
Per unit length series Inductance	ℓ	**mH/km**	*0.204*
Per unit length shunt Leakance	g	**nS/km**	*negligible*
Per unit length shunt Capacitance	c	**μ F/km**	*0.0545*
Characteristic Impedance	$\underline{Z}_0$	**Ω**	*61.46 ∠ -0.07 rad*
Propagation Factor	$\underline{k}$	**1/km**	*0.0001 + j 0.001*
Surge Impedance Loading at 400 kV	**SIL**	**MVA**	*2604*
Capacitive current related to $U_o = 400kV/\sqrt{3}$	I_{cap}	**A/km**	*3.95*
Ampacity	I_c	**A**	*2.4 ÷ 3 kA It depends upon the installation*

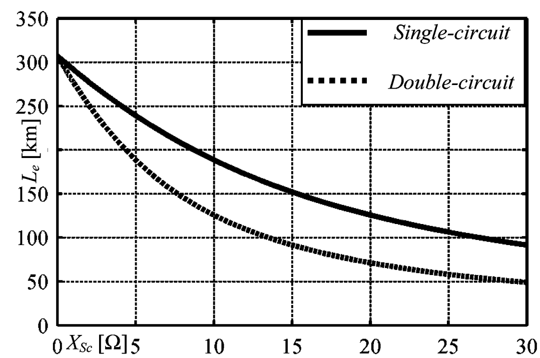

Fig. 9. No-load real limit lengths as a function of short-circuit impedance.

where $-jX_C = A_{id}/\underline{C}_{id}$ is the capacitive impedance of the GIL.

In regards to X_{Sc} evaluation, it is possible to refer to the subtransient impedance U_o^*/I_{Sc}'', giving the subtransient current I_{Sc}'' (three-phase at S) the foreseen highest values (≈50 kA $\rightarrow X_{Sc} = 4.6\ \Omega$) and lowest (≈10 kA $\rightarrow X_{Sc} = 23\ \Omega$) in the 400-kV network.

Due to the capacitive nature of the load X_C at S and the Ferranti's effect at $R, |U_{oR}| > |U_{oS}| > U_o^*$ will be always verified so that in any case, the phasor U_{oR}, computed by means of (2), will not have to exceed the magnitude 242.5 kV $= U_m/\sqrt{3}$. The length for which this occurs is the real length L_e. Fig. 9 shows L_e as a function of the short-circuit impedance for the single- and double-circuit GIL: when the network is strong, the limit length is rather high both for single-circuit and double-circuit whereas when the network is weak (namely with three-phase short-circuit currents up to 15 kA), the limit length reduces considerably. So this is the most restrictive criterion and has to be verified in each situation.

Also, the other criterion, which deals with the power capability, is few limiting: both Fig. 10 (d = 120 km) and Fig. 11 (d = 240 km) highlight that GILs are suitable for bulk power transmission (chosen ampacity I_c = 2400 A). This good behavior fades slightly up to 300 km.

The ultimate retained criteria are the voltages and currents along the GIL: the current magnitudes never exceed the am-

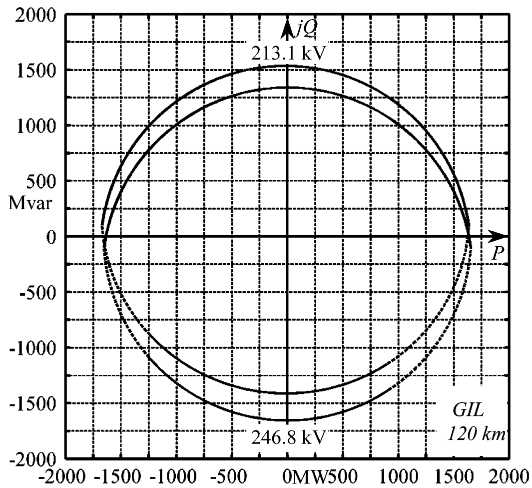

Fig. 10. Power capability chart for GIL; $d = 120$ km.

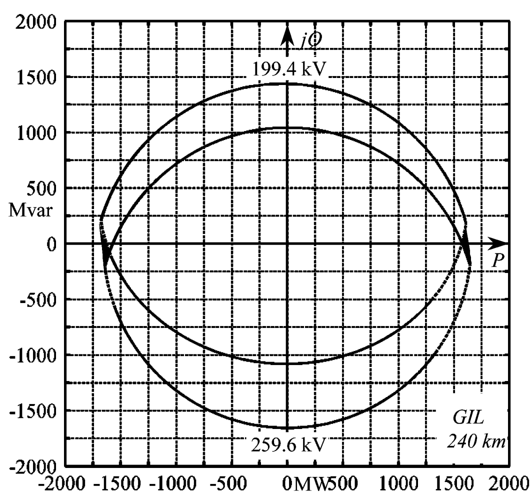

Fig. 11. Power capability chart for GIL; $d = 240$ km.

pacity whereas the regimes exceeding the voltage limit are highlighted in Figs. 10 and 11 by means of gray lines. This confirms the well-known difficulties to transmit high reactive power flows over long distances. The capability charts (along with "gray warnings") computed for higher ampacity (e.g., $I_c = 3000$ A) would show shorter length limits ($100/150$ km).

IV. GIL in Structures

The possible structures involved in GIL installations are:

- bridges;
- tunnels;
- electric tunnels;
- traffic tunnels;
- railroad tunnels;
- other kind of tunnels.

In the following, some GIL features are highlighted in order to show the compatibility with tunnel installation.

- The environmental impact (visual and "magnetic") of a traditional overhead line (single or double circuit) is already considered undesirable by society. GIL solution zeroes the visual impact (as XLPE cables).

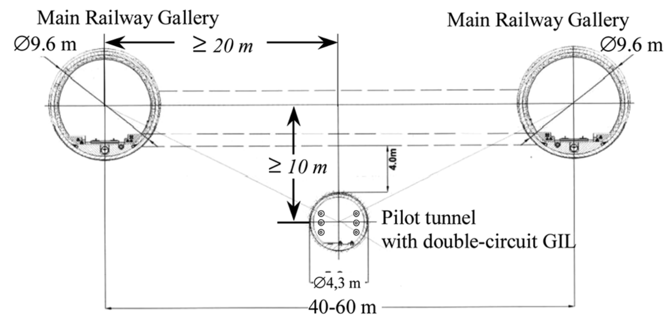

Fig. 12. Sketch of main railway galleries and of the pilot tunnel (Brenner Basistunnel EWIV).

- High safety: in case of an insulation failure, there is not an explosion, which could damage adjacent conduits or other nearby installations and persons. GIL manufacturers have to guarantee, for an internal fault, a rated short-time withstand current according to IEC 61640 (i.e., 63 kA for 3 s).
- High reliability: the GIL technology has proven its reliability since being 25 years in service without any failure up to now. The main reasons are the dielectric stress in the material is very low ($3/4$ kV/mm), and the GIL has no special joints, which are usually critical elements. It is worth noting that the reliability of long runs is wholly unknown due to a lack of long GIL installations.
- No aging: Gases are not aging, neither thermal nor electrical.
- SF_6/N_2 gas mixtures: these mixtures are long-time experienced insulating gases and used worldwide in high-voltage technology.

V. First Possible Application: Double-Circuit GIL Installed in the Pilot Tunnel of Italy–Austria Railway Galleries

An important application of the GIL in structures is represented by the idea of installing a double-circuit GIL in the pilot tunnel of the new planned railway galleries between Italy and Austria through the Brenner Pass. A view of this application has been given in [4]. Two separate tunnels (see Fig. 12) will constitute the railway galleries (one for each railway track) and a pilot tunnel will precede the main tunneling in order to detect the geologic situation of the rock stratigraphy. Once the whole work is over, the pilot tunnel will be used as a service gallery: this 4.3-m diameter gallery (see Fig. 13) can be efficiently used to install a double-circuit GIL. On the contrary, the direct installation inside each proper railway gallery (see the 9.6-m diameter main railway galleries in Fig. 12) of a single-circuit GIL (2.0 $\times$ 0.7 m) would only require a new design to foresee a suitably deep area underneath the railway tracks. The conductor vertical arrangement (see Fig. 13) is fully compatible with the pilot tunnel, which could also host medium-voltage (MV) and low-voltage (LV) cables, fiber optics, and the mole drain. In order to avoid excessive unit movement, a service rail (SR) and some intermediate accesses are foreseen.

The enclosures should be systematically bonded together and with the steel reinforcement of the gallery at very short length

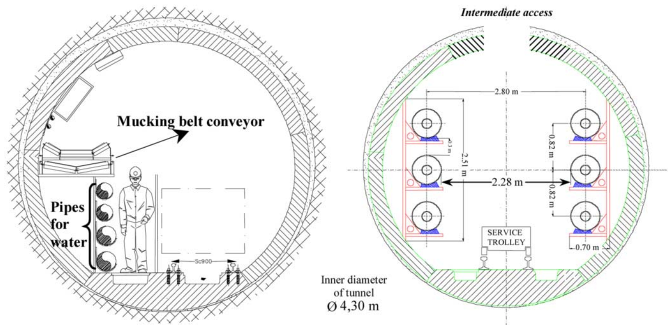

Fig. 13. Sketch of PILOT TUNNEL during the main gallery excavations and with double-circuit GILs.

intervals; this ensures equipotentiality between the tunnel wall and the GIL enclosures and constitutes a very good distributed earthing so that the touch voltages inside the gallery are zeroed even during a single-phase fault (so ensuring complete safety for operators employed in GIL inspection).

VI. Further Investigations of CIGRÉ Joint Working Group

As already mentioned, a CIGRÉ Joint Working Group has begun. The scope of the group is to deeply analyze this novel approach of integrating electricity transmission and railway, highway (or other) systems in the same structure. Members are coming from ten different countries.

In the following, the contents which will be assessed by the JWG are reported.

A. Thermal Behavior of GIL Inside a Tunnel

The thermal behavior of a GIL (single or double-circuit GIL) inside a gallery deserves careful consideration. It should be remembered that IEC 61640 [13] recommends that the maximum allowable temperature for the enclosure shall not exceed 70 °C. By means of the matrix integral algorithm, the Joule power losses W/m in both phases and enclosures can be precisely evaluated taking into account the proximity effect.

There are a lot of formulae in literature [14], [15] which allow evaluating the phase and enclosure temperatures but do not take into account the temperature profile inside the gallery and the possibility of the gallery ventilation.

B. Setting Variation in Distance Protections

It should be noted that the interface between GIL–OHL is not a problem in regards to reclosure cycles so that no change is needed in the relay schemes. The GIL insulating medium is self-repairing (i.e., it restores its insulating properties after a disruptive discharge). The GIL operation is similar to that of OHL: so GIL could be an ideal addition to OHL. The very fast transient overvoltages have been investigated in [16].

C. Power Flow and Short-Circuit Studies

The addition of a GIL line in the EHV network constituted almost exclusively by OHL makes it necessary to deeply examine the GIL influence on power flows, short-circuit levels, and voltage stability. The high transmission capability of the GIL ensures that it will not be a bottleneck when inserted in an existing OH transmission network. The other contents are the following:

- handling of large-scale projects and deliveries;
- mechanical layout;
- testing on site;
- repair process;
- safety and reliability analysis;
- electromagnetic interference with other electrical systems.

VII. Costs

The installation cost of the gas-insulated lines is sensibly higher than that of an overhead line. In regards to extra high voltage ($U_m = 420$ kV), a single-circuit overhead line costs about 400 keuro/km against 2.4 Meuro/km of a single-circuit GIL. Moreover, as shown in Italian literature [17], [18], the economic convenience of the GIL compared to overhead transmission lines is highlighted when power losses and territory constraints are accounted for. In fact, the resistive losses are significantly lower compared to overhead lines, and the dielectric losses are wholly negligible. This could reduce the transmission costs significantly. The major role in comparative analysis is played by territory constraints owing to magnetic-field limitation imposed by law. More restrictive are the magnetic-field limitations imposed by the state as more convenient GILs are compared with other EHV transmission systems.

VIII. Conclusion

In this paper, the authors, who are convener, secretary, and member of JWG CIGRÉ B3-B1.09 "Application of Long High Capacity Gas Insulated Lines in Structures," have focused on the possibility of installing gas-insulated lines in multipurpose or dedicated structures as highway or railway galleries, bridges, and so on.

This paper highlights the actual installation in the tunnel and some ideas of application of the binomial GIL structures.

Moreover, the knowledge about GIL analysis and the future investigations that will have to be tackled are reported.

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