

# GAS INSULATED TRANSMISSION LINES (GIL) WITH SPARE PHASE – NEW CONCEPTS FOR INVESTMENT REDUCTIONS

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## 1. SPARE PHASE CONCEPT

Up to now, for EHV transmission systems of power utilities often the N-1 principle has been used for planning purposes [1], both for planning in network development and operation. For Germany this is for instance regulated in [2] and [3]. This deterministic principle means in the context of transmission lines that in the case of an outage of one line the whole grid must not result in neither further outages nor in overloading of one system [4]. For traditional three phase AC systems the n-1 criterion is often fulfilled by installing two parallel AC system being capable of carrying the full load of the connection. During normal operation the two systems are often operated in parallel, each with half the total load. In case of an outage of one system the other one carries the full load.

With very long distances the application of two full systems because of reliability reasons is limited due to economical limits. For this, different solutions exist which allow the compromise of reliability and economic requirements [5, 6, 7]. Among others, one measure for increasing the reliability of a single three phase system is the use of an additional spare phase. In the case of a line-to-ground fault, which represent more than 95% of the causes for transmission system faults [5], the defective line is removed from the net and the additional spare phase takes the function of the removed line. After repairing the defective one, the system can be brought to the same availability status again.

## 2. GIL WITH SPARE PHASE

### 2.1 Spare Phase with GIL

Gas Insulated Transmission Lines (GIL) have often been described in the past. They are a means of bulk power transmission in the EHV range where overhead lines (OHL) are not applicable and where cables reach the limits of their transmitting capacities. The typical range of rated voltages is between 230 kV and 550 kV with rated currents between 2500 A and 4000 A respectively. The latter range depends on the laying concept (directly buried, outdoor or tunnel application). Typical application examples for GIL are the cross connection of busbars for some 100 meters with

the extension of outdoor substations or the replacement of OHLs for some kilometers because of environmental reasons.

As mentioned in the previous paragraph, most of the faults happening with OHLs are line-to ground-faults. They may be caused by lightning strikes or falling trees during thunderstorms. These reasons for faults usually are not relevant for GIL. With underground installations trees or similar things are no threat and with a sufficient insulation coordination with the according application of surge arresters also lightning strikes mean no harm for the insulations system of a GIL. Therefore, the probable risk of single-phase-faults is decisively lower than that of OHLs. The operational experience of more than 30 years show that once a GIL is successfully tested and commissioned there is no further insulation fault. Further, due to the encapsulated concept of GIL the extension of a single-phase-fault to a multiple-phase-fault is very unlikely with a GIL. As a consequence, in order to achieve approximately the same reliability of a double system GIL only a further spare phase with a suitable switching unit has to be applied. Fig. 1 shows the basic concept of applying a spare phase system between two busbars for instance.

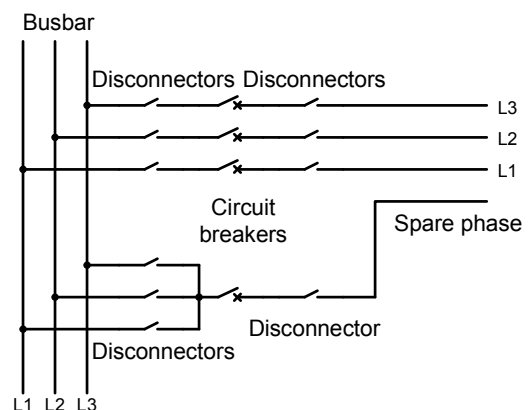


Fig. 1: Basic concept of GIL spare phase

During normal operation the disconnectors and the breakers of the main phases are closed, the switches of the spare phase are open. In case of a fault in one main phase the main circuit breakers are opened. In the spare phase the according disconnector of the “defective” phase and the disconnector on the GIL side are closed. After that,

the breakers of the sound main phases and that one of the spare phase are closed. After repairing the defective phase the original status can be restored.

The switching process may last up to two minutes if switches are applied like in fig. 1. This means that the line is off the grid for approx. one to two minutes. If this outage time is too long the concept shown in fig. 2 may be applied. This system allows the rapid switching from the defective to the spare phase with switching period in the range of 300 ms. Such switching durations are similar to those happening when automatic reclosure (ARC) is applied.

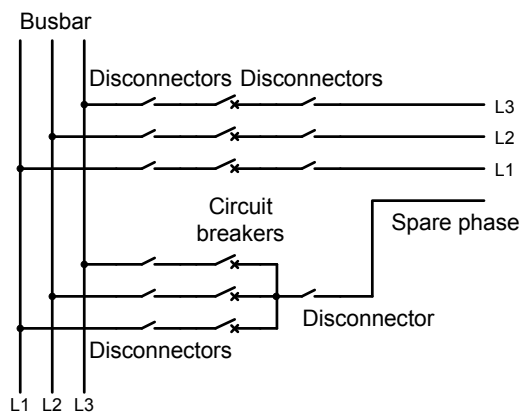


Fig. 2: Rapid time switching spare phase system

During normal operation the switches in the main phases are closed. During normal operation the disconnectors of the spare phase are closed to prepare it for rapid switching and the circuit breakers of the spare phase are open. This is the stand-by status. In case of a fault in one of the main phases the protection system removes the defective phase with the according circuit breaker and the spare phase is activated by closing the according circuit breaker with the busbar of the “defective” main phase. This switching process can take place within 300 ms like described in section 2.4. As shown in section 2.2, this switching system results in superb reliability figures. With the length reduced capacitance of  $C' = 55 \text{ pF/m}$  a capacitive switching current of  $I_C = 400 \text{ A}$  results for a 400 kV GIL-section of approx. 60 km. This current can be handled with standard circuit breakers so that the charging current is not a factor against this concept.

Due to the closed disconnectors in the spare phase, the latter has to be regarded as “switched on” during stand-by operation. Due to the encapsulated design, however, this does not cause any harm neither to operational personnel nor to the installation itself.

As described above, during stand-by operation of the arrangement of fig. 2 the disconnectors of the spare phase are closed. Therefore, the full operating voltages and the possible overvoltages respectively are present at the poles of the circuit breakers. In the case that this arrangement should not fulfill the safety requirements given by the operation principles or the philosophy of a utility, circuit breakers can be used which also fulfill the disconnecting function [8]. Such apparatus are available for the voltage range from 145 kV up to 420 kV from different manufacturers [9, 10, 11]. By this, the rapid switching process from a defective to the spare phase is possible without any reductions concerning safety issues. Fig. 3 shows the basic switch arrangement at a busbar of a substation.

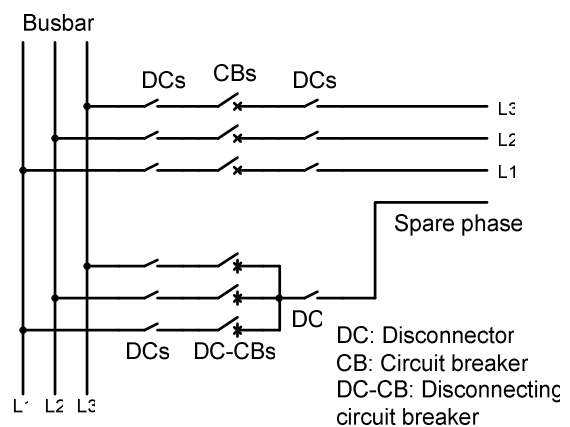


Fig. 3: Spare phase with disconnecting breakers

During stand-by operation the additional disconnectors in the spare phase which are necessary for maintenance purposes at the breakers are closed. The disconnecting function of the breakers ensures maximum safety.

## 2.2 System reliability

The reliability of a system with rapid switching will be quantified by an estimation based on a probabilistic calculation. As mentioned above, due to the encapsulation almost only single-phase-faults have to be considered for the reliability of a GIL. Therefore, for reliability calculations only the reliability of a single phase and not the reliability of three parallel lines will be regarded. The reliability of a single GIL phase may be calculated by applying the more than 30 years enduring operational experience of the existing GIL installations and the almost 40 years of operational experience with GIS busbars. As described in [12, 13], the reliability of a GIL phase can be calculated by means of its availability. The availability is generally found to be

$$A = \frac{MTBF}{MTBF + MTTR}, \quad (1)$$

with MTBF being the Mean Time Between Failure and MTRR the Mean Time To Repair. From the operational experience gained with GIL and GIS respectively, for Siemens-GIL a length reduced value  $MTBF^*$  is estimated to be

$$MTBF^* = 400 \text{ kmYears.} \quad (2)$$

Therefore, for a GIL of, say, 10 km a value of

$$MTBF = 40 \text{ Years} = 14600 \text{ d} \quad (3)$$

can be found. Assuming for the worst case (which includes the replacement of a 50 m long GIL section) a maximum repair period of approx. 20 days, for a single phase of the 10 km long GIL an availability figure of

$$MTBF_{10km} = 99.85\% \quad (4)$$

can be found. For an arrangement according to fig.1, however, the reliability number of a 10 km long section will by far be higher since the outage period will not be 20 days. It will only be approx. up to two minutes until the spare phase is connected to the net. Should this, however, also be too long for a stable net operation, an arrangement according fig. 2 or fig. 3 can be used. In any of these cases the outage time is in the range of 300 ms. This is in the range of the outage times during ARC. Applying this figure for calculating the MTBF-number according to formula (3), the superb value of

$$A > 99,999\% \quad (5)$$

results.

In the status with the spare phase “on” and the defective phase “off” the theoretic reliability of the system is reduced since no reserve is present. However, due to the inherently very high reliability of GIL this normally is not a real problem since GIL may be repaired in a very short time. The probability of occurring a further failure right in the repair period is rather low.

### 2.3 Combination of GIL and OHL

Typically, the application of GIL is intended for cases where OHLs cannot be employed. This may be, for instance, in the proximity or within conurbations where aesthetical, ecological or economical reasons are in favor of underground solutions. GIL can also be applied for the replacement of certain sections of overhead lines. For instance, in Geneva a section of 400 m of an OHL was replaced by a GIL for the reason that the space where the OHLs were installed were intended for different applications. Several similar

cases with GIL sections in the range between 2 to 10 km are evaluated presently in Europe.

The rated currents of OHLs are typically between 2000 A and 3000 A. Operating a double system of 3 phase OHL means operating currents of 1500 A per system. If one system fails, the other one takes the full load. GILs have been designed for high currents. Depending on the application, a GIL system may carry between 2500 A (directly buried) and 4000 A (tunnel or outdoor installation) of continuous current [14]. The application of a thermal rating system allows even in the case of directly burying currents of up to 4000 A for operating hours with higher currents [15]. Therefore, for the replacement of OHLs for certain lengths with GIL, instead of applying a double system of GIL (6 phases) only a 3-phase system with a spare phase as described in section 2.1 may be applied. Fig. 4 shows the switching concept.

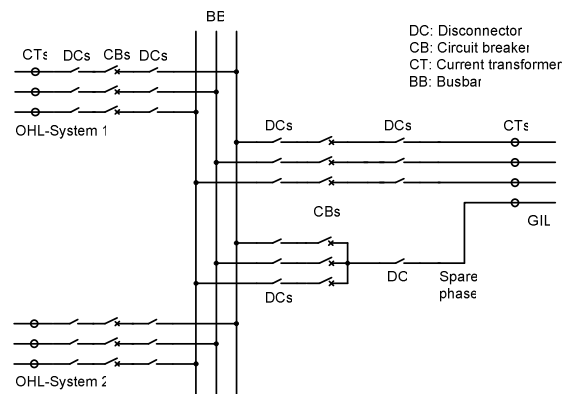


Fig. 4: GIL with spare phase in the line of OHLs

The incoming OHL system are switched with conventional disconnectors and circuit breakers to a busbar. From this busbar the GIL with spare phase is fed according to the principle of fig. 2 and fig. 3 respectively. In the case of a failure on the GIL the spare phase can be activated as mentioned in the previous sections. In the case of failures on one of the OHLs these can be cleared with the breakers on either end. Also ARC is possible. The current transformers shown in fig. 4 are necessary to enable the protection system to activate the relevant switches. The protection scheme is described in section 2.4. The application of this concept requires, contrary to a double system of GIL, an additional switching system. This solution, therefore, makes sense from the economical point of view when the savings caused by this principle are higher than the additional investment. Economical aspects are described in section 3.

## 2.4 Schemes for protection and control

The goal of the protection concept is the selective detection of failures in the range of the GIL and to ensure the reliable energy transmission by energizing the spare phase. By applying the principle of differential protection it is possible to detect short circuits in the protection range selectively for each phase. Digital differential protection devices measure the currents at either end of the conductor and exchange this information with the remote end by means of optical fibres. This protection scheme is shown in fig. 5.

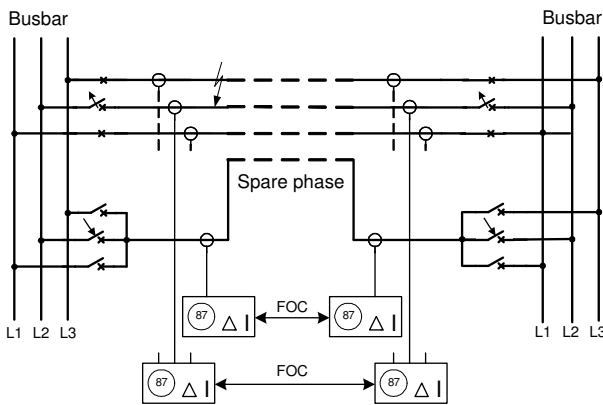


Fig.: 5 Scheme for protection

During regular operation all disconnectors are closed. Once the protection device recognizes a failure the circuit breakers at both ends of the relevant phase receive the breaking command within 35 ms at most. At the same time the circuit breakers of the spare phase are chosen. The closing commands of these breakers are released after the circuit breakers of the defective phase are open and the breaking arcs are extinguished. This condition is recognized by recording the decrease of the fault current and the feedback signals of both breakers. The break time of the circuit breaker is approx. 60 ms. For energizing the spare phase additionally the closing time of the circuit breaker of at most 75 ms has to be considered. Depending on the used logic components and the chosen safety margins the spare phase is available for operation latest after 300 ms. The switching process can be realized by both, the application of rapid relays or programming of switching relays.

## 3. ECONOMIC BENEFITS

### 3.1 Reduced investment costs

In these cases where a single system of GIL with spare phase can successfully be applied instead of a double system, starting from a minimum length the investment costs are reduced remarkably. Primarily, instead of six phases of GIL only four

phases need to be installed. This results in reduced costs for installation and commissioning of approx. 30%. Depending on the type of installation also the costs for civil works are more or less reduced. With outdoor installations the support structures are less costly. Their costs are also reduced for approx. 25% to 30% due to the reduced number of GIL pipes. With direct buried or tunnel installations, however, the absolute share of civil costs of the total costs are remarkably higher. As an example, fig. 6 compares the tunnel sizes of a 6 phase and a 4 phase system.

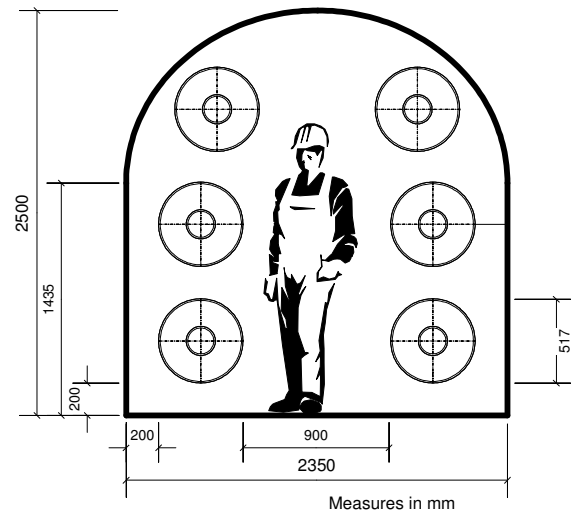


Fig. 6a: Tunnel size for 6 phases GIL

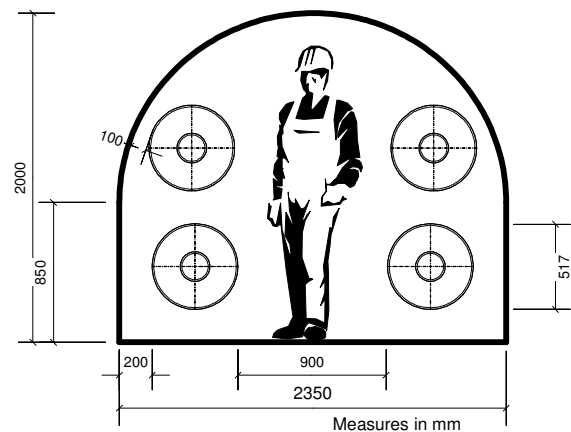


Fig. 6b: Tunnel size for 4 phases GIL

The comparison shows that with 4 phases not only the material necessary for the tunnel is reduced by approx. 13%. Depending on the trench profile for the tunnel erection savings of 20% to 30% are possible due to the reduced soil volume which needs to be moved. Similar savings are possible for rectangular tunnels with open-cut installation or with bored tunnels with round cross sections. For the latter also cost savings of 30% for the civil

portion can be achieved. Summing up the relevant costs, with 4 phases average cost savings of 25% to 30% compared to 6 phases are achieved.

Contrary to the mentioned cost savings, the spare phase concept also has additional costs for the switchgear arrangement. From the economical point of view the spare phase concept makes sense first when the price reductions for installation, commissioning and civil works are higher than the additional costs caused by the switchgear. All these savings and costs depend on several factors, like switchgear concept (AIS, GIS, HIS), laying method and depth, soil conditions etc. Therefore, a breakeven value for the minimal economic length which has general validity cannot be given. But assuming average values for laying conditions and depths and assuming standard switchgear solutions the breakeven starts at lengths between 1.5 and 2 km. This means that depending on the boundary conditions already from a length of more than 1.5 km the spare phase concept results in absolute cost savings.

### 3.2 Lifecycle costs

Unlike the investment costs, the operational costs of a 4 phase GIL are normally higher than those of a 6 phase double system of GIL. This is because the operating current is only 50% of the totally transmitted current in the case of a 6 phase system but 100% in the case of a spare phase system. Therefore, the ohmic losses of the 4 phases are up to two times higher than those of a double system. Indeed, by increasing the wall thicknesses of the GIL pipes the losses can be reduced but there exist limits. In the case of tunnel installed GILs also a ventilation system might be necessary to remove the dissipating heat which causes additional losses. Due to the fact that GIL systems demand only very little maintenance the lower efforts for maintaining the 4 phase system may be neglected. As a consequence, the operational costs of a 4 phase system may generally be regarded as higher than those of a 6 phase system.

For the calculation of life cycle costs not only the operational costs should be regarded. Assume that the application of a 4 phase system results in cost savings of 25% compared to a six phase system. The saved money can further be invested. The interest resulting of these investments has to be deducted from the higher operational costs for the intended operation period, even if these interests are only fictive in the case the savings are used for different investments. By this, the higher operational costs are compensated.

For purposes of appraisal of investment projects often the net present value (NPV) method is used. It uses a target rate of return or cost of capital to

discount cash flows happening during the project life time to their present values [16]. This method considers the risk of a project, the effects of inflation and the interests which would be achievable with different investment projects of lower risk [17]. Similar to such a project appraisal, the savings achievable with the spare phase concept can roughly be estimated as shown in the following example. However, the inflation factor is not considered since both the savings and the additional costs suffer the same inflation factor so that this parameter is not relevant for a rough comparison.

Assume a 10 km long transmission system with a rated current of  $I_r = 1800$  A realized as a double system of GIL. Assume further 2500 h of full load to calculate the total annual transmission losses. For this calculation the costs for the losses are assumed to have a level of 50% of the average electricity market price. Using these assumptions, the annual transmission losses  $L$  in the first year after installation may be estimated to be approx.

$$L = 0.003 \cdot K, \quad (6)$$

which is 0.3% of the total investment  $K$  of the double system of GIL. The investment  $K$  and the rates for the costs of the losses are based on average price in 2005. Assuming an annual increase of energy costs of  $inc = 2\%$ , the total sum of the transmission losses after 30 years of operation  $L_{30}$  can be estimated to be

$$L_{30} = \sum_{k=1}^{30} (L \cdot 1.02^k) = L \cdot 40,57 \approx 0.12 \cdot K \quad (7)$$

When a GIL with spare phase is applied the total losses after 30 years results in double the sum of (7) since the rated current being twice that of the double system of GIL. This means that after 30 years the spare phase system causes additional costs for transmission losses  $L_{A,30}$  of

$$L_{A,30} = 0.12 \cdot K. \quad (8)$$

However, as described in section 3.1, with the spare phase concept savings of 30% of the investments are possible. Assuming this number and deducting 5% of this to finance the switchgear on either end, a total investment saving  $K_s$  of

$$K_s = 0.25 \cdot K \quad (9)$$

is realistically achievable. Investing this sum in a safe investment project with an annual interest rate of  $int = 9\%$ , this investment saving results after 30 years of investment in a total sum  $K_{s,30}$  of

$$K_{s,30} = K_s \cdot 1.09^{29} = K_s \cdot 12.17 \approx 3 \cdot K. \quad (10)$$

Comparing this number with the additional losses of equation (8) shows that the savings are by far higher than the additional costs. Even when assuming an interest rate of only 6% of a secure investment, the savings still are ten times higher than the additional costs. This points out that the spare phase solution is a viable concept which definitely results in cost savings along the life cycle.

Sensibly, the savings are usually not directly invested in pure investment projects but are used for different operational purposes. But this fictive calculation is only to show the real savings achievable with the spare phase concept.

#### 4. CONCLUSION

The application of the well-known spare phase concept to GIL with the according switching units enables the chance of reduced investment and lifecycle costs without reduction of reliability. The sensibility of this solution and the savings achievable depend on the boundary conditions of each project. From the present point of view, a system length of approx. minimum 1.5 km to 2 km is necessary to achieve real savings. However, already below this threshold this concept may be successful in some cases.

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