Comparison of GIS and AIS systems for urban supply networks

Studies carried out by ABB show that for urban supply networks the combination of HV gas-insulated switchgear (GIS) and HV cable has important advantages over systems with air-insulated switchgear (AIS) and overhead lines. Due to their compactness and flexibility, GIS substations can be located close to load centers, allowing a much more efficient configuration for both the HV system and the MV distribution network. The saving in investment and operating costs more than compensates for the higher cost of the GIS and cables. Benefits include higher reliability and the option of integrating a complete GIS substation in an existing building, eg when extra site area is not available.

Besides the vital role they play in modern market economies, electricity supply systems also have a large impact on the environment, making them subject to changes in social paradigms. It is in part due to this that the medium-voltage systems supplying power to urban areas are designed today almost entirely as cable networks with indoor switching stations. Besides its reduced visual ‘intrusion’ on everyday life, gas-insulated switchgear (GIS) also offers operators of high-voltage supply systems reliable and flexible solutions in areas where load densities are high and substation sites have to be kept small. Urban supply systems combining GIS technology and HV cable are safe, reliable and environmentally benign.

A direct comparison of the component investment for identical switchgear configurations suggests that the GIS variant is more costly than the air-insulated switchgear (AIS) solution. However, such a comparison does not take into account the fact that by locating a GIS transformer substation close to the load centers a far more efficient network structure is obtained at both the HV and the MV distribution level. As a result, the investment and operating costs are reduced.

To quantify the respective impact of AIS and GIS technology at the HV and the MV levels of an urban supply system, a look is taken in the following at an existing network with a maximum load of 120 MW. The MV network is optimized for each of the HV variants (GIS and AIS), in each case for distribution voltages of 10 kV and 20 kV, so that four different HV/MV networks are evaluated. The comparison is based on the life-cycle costs of the different supply concepts.

Design of the AIS/GIS network variants

High-voltage network

The best locations for the HV injections into the distribution network depend to a large extent on the technology (AIS or GIS) chosen for the HV system. Sites which are large enough for AIS substations are seldom available, and when they are their cost is extremely high. But it is not just the smaller size of the site that makes GIS the lower-cost option: GIS is also the more economic alternative when expanding or replacing existing substations. An inner-city site that has been used previously for an AIS installation can be sold or rented out and the income used to help finance the new substation. The compactness of GIS enables an HV transformer substation to be fully integrated in an existing building, which may only have to be made higher or have a basement added.

The issue of space extends beyond the transformer substations to the high-voltage connections. Overhead lines are today practically ‘no-go’ as an option for inner-city areas. And even where rights-of-way are available, these can often be utilized more economically in other ways. Typical complaints about overhead lines are that they are unsightly and generate electromagnetic fields, the effects of which are subject to constant and intensive public debate.

Modern-day HV cable not only offers a high level of reliability but also some technical benefits for overhead line connections. Given these advantages, there is today no realistic alternative to HV cables for electric supplies in urban areas.

Werner Zimmermann
André Osterholt
Dr. Jürgen Backes
ABB Calor Emaq Schaltanlagen AG
Use of ABB gas-insulated switchgear allowed the 132-kV transformer substation Barbaña in the center of Orense, Spain, to be constructed underground and a park built over it which harmonizes with the surroundings. The sound of the waterfall, which acts as a heat-exchanger, hides the noise made by the fans.

GIS

The GIS variant considered in the study consists of three HV transformer substations located in the center of a city. The connection to the surrounding 110-kV network is provided by three cables run from the nearest HV substation to the main substation of the urban HV network. This main substation is configured as a double busbar system, allowing maintenance to be carried out on one busbar without having to de-energize the complete station. The remaining substations in the HV cable ring, which are also located in the city center, are H-type transformer substations with a bus-tie. They also allow maintenance and repairs within the gas compart-
AIS

In the AIS variant there is an overhead line loop around the supply region, the right half of which consists of double lines (due to the load flows). As in the GIS variant, the main HV substation consists of a double busbar system, the remaining HV transformer substations having H-type configurations. Transformer substation TS2 has a double-T connection to the double overhead line, substation TS3 being looped into the single line on the left-hand side. Due to the larger space required, the transformer substations are located in the less densely populated outer regions of the city.

Double lines connect the outer ring to the transformer substations, i.e. there are two circuits on the same poles. This solution allows efficient utilization of the available space. However, it also reduces the reliability of the HV supply as both circuits can trip for the same reason ("common mode failure", e.g. due to back-flashover from the earth wire to both circuits caused by lightning striking the earth wire or contact with trees).

Medium-voltage network

A comparison of the GIS and the AIS variants based only on the differences in the HV network is too limited, since the locations of the HV transformer substations are of decisive importance and exert a large influence on the structure of the MV network. The study therefore takes the load situation in an actual urban network, including the load values and the geographical location of the MV transformer substations, as its starting point.

Radial operation of an MV network results in a large number of possible network concepts. Besides differing in terms of their initial capital costs, they also considerably influence operation of the network. Each utility therefore has its own planning rules, according to which the network configuration is adapted to customers' requirements and to the geographic locations of the MV loads.

Planning rules

The technical constraints for each network variant are the allowed voltage band and the limits for the short-circuit power, which are dictated by the rating of the switchgear. There are also some design rules to be formulated:

- Use of standard components:
  - XLPE MV cables with an Al cross-section of 150 mm² (distribution cables) and 240 mm² (transmission cables)
  - 110-kV/MV transformers with a rated power of 31.5/40 MVA
- Open-loop topology for the distribution network. The distribution cables start from the MV busbar of the HV/MV transformer substations, run between customers’ substations and are looped back to the MV busbar of the same HV transformer substation. During normal
operation one of the cables in this ring remains open to provide simple protection. Each HV/MV transformer substation has its own back-up transformer, allowing maintenance to be carried out on a transformer without having to operate switches in the MV network.

- Maximum of 14 customer substations in a loop. This limits the number of customers whose power supply would be interrupted in the event of an MV network failure, as only the feeder connected to the HV/MV station busbar is equipped with overcurrent protection and a circuit-breaker.
- Normal loading of the feeder cables, so that a worst-case cable failure (feeder failure close to the HV/MV transformer substation) does not load any cable beyond 120% of its capacity. The maximum load of 5.2 MVA per cable at 10 kV (10.2 MVA at 20 kV) at the beginning of the planning period takes into account the reduced ampacity for cables bundled in the same cable trench close to the transformer as well as a margin for load growth during the planning period.

Planning results
The inherent flexibility of GIS allows planners to place the injection points close to the load centers. The first effect of this is on the number of loads considered an optimum for each HV substation, and thus on its installed transformer capacity. Secondly, it reduces the required power transmission capability of the MV network, allowing an additional saving due to the smaller MV cable cross-sections required. And thirdly, transmission losses are avoided. The reduction in operating costs due to this third advantage is especially evident at low distribution voltages.

These general effects are also reflected in the results obtained with the described network solutions. The MV network receiving power from the GIS substations consists of radially operated (open) loops, all of which are fed from the MV busbars of the HV substations.

The peripheral locations of the transformer substations in the AIS variant make additional satellite stations necessary. These have remote MV busbars, fed by the HV transformer substations via several parallel and selectively protected transmission cables. Their reliability is comparable with the reliability of the MV busbar of the HV transformer substations, but they call for extra capital investment and cause additional losses. The AIS variant with a voltage of 10 kV requires 6 parallel cables from the HV injection to the satellite station, the 20-kV variant requiring 4 cables. These satellite busbars, like the MV busbars of the HV substations, supply power to the MV substations via open loops.

**GIS/AIS cost comparison**

[7] and [8] compare the respective cost of the AIS and the GIS variant (the figures for the different components and external services apply to the German market). An interest rate of 8% and an inflation of 3% were assumed for the calculation of the cash values. A load growth of 1.5% per year (linear) was set and the cash value calculated for a planning horizon of 10 years. It should be noted that planning times of 20 years and more, which have...
often been used in the past to evaluate different variants, are not realistic in today’s rapidly changing market environment.

The first cost to be considered in the comparison is that of the HV switchgear installations. This is significantly higher for the GIS than for the AIS solution. However, the difference in system costs is smaller than the difference in component (e.g., switchbay) costs. This is because the inherent flexibility of the GIS/cable topology allows the HV network to be configured more efficiently, leading to a smaller number of HV substations (3 for GIS, 4 for AIS) and also switchbays per HV transformer substation.

A look at the cost of the 110-kV connections shows a similar picture. Although the cable length in the GIS variant is much shorter than the length of the overhead lines with AIS, the capital cost of the equipment and civil works are higher in the case of GIS.

The difference in the cost of the 110-kV transformers results from the different number of transformers in the two variants. In the case of GIS, two transformers are required at substation TS1 for normal operation, so that only a single additional unit is necessary for back-up. The AIS variant requires a dedicated back-up unit for the transformer in each HV substation.

Comparison of the cost of the GIS and AIS variants (cash value over a period of 10 years)

<table>
<thead>
<tr>
<th>Substation</th>
<th>GIS (20kV)</th>
<th>AIS (20kV)</th>
<th>GIS (10kV)</th>
<th>AIS (10kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switchgear</td>
<td>110 kV</td>
<td>110 kV</td>
<td>110 kV</td>
<td>110 kV</td>
</tr>
<tr>
<td>Lines/cables</td>
<td>110 kV</td>
<td>110 kV</td>
<td>110 kV</td>
<td>110 kV</td>
</tr>
<tr>
<td>Transformers</td>
<td>110 kV</td>
<td>110 kV</td>
<td>110 kV</td>
<td>110 kV</td>
</tr>
<tr>
<td>Switchgear</td>
<td>110 kV</td>
<td>110 kV</td>
<td>110 kV</td>
<td>110 kV</td>
</tr>
<tr>
<td>Cables</td>
<td>MV</td>
<td>MV</td>
<td>MV</td>
<td>MV</td>
</tr>
<tr>
<td>I &amp; C</td>
<td>Land/</td>
<td>Construction</td>
<td>Maintenance</td>
<td>Repairs</td>
</tr>
<tr>
<td>Losses</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interruption costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Topology of the GIS variant with injection points close to the load centers (distribution voltage 20 kV)**

TS1, 2, 3  Transformer substations 1, 2, 3

**Topology of the AIS variant with peripheral transformer substations and additional satellite stations (distribution voltage 20 kV)**

TS1, 2, 3, 4  Transformer substations 1, 2, 3, 4
Another factor that speaks for the GIS variant is the cost of the MV switchgear installations. The difference here is due to the additional switchgear panels needed for the satellite stations in the AIS configuration.

The cost of the MV cables is extraordinarily high for both variants (about 40% of the life-cycle costs/cash value). Their absolute value as well as the difference between AIS/GIS shows how important it is to compare complete supply concepts rather than just the HV substations if results are to be reliable and realistic: HV injection close to the load centers reduces the MV network costs significantly.

The smaller number of HV substations, the absence of remotely controlled MV satellite stations and the reduced number of HV connections also reduce the cost of the secondary equipment (ie, for protection, control and instrumentation) for the GIS variant.

In addition, the cost of the land, foundations and buildings is lower for the GIS variant. This is due to the smaller space required, which can even compensate for the higher cost of land in the inner city. Also, the GIS substation can be integrated in the basement of an existing building, thus providing the required space without having to add to the footprint. Since this solution is still unusual in Germany, it has not been considered in the comparison. In South-East Asia and other regions, utilities often take advantage of this option in order to install HV stations in highly populated load centers.

The difference in the cash value of the losses quantifies the additional transmission loads in the MV network. A saving of approximately 25% is possible with GIS. It is costs such as these that underscore how much the results depend on the basic assumptions of the comparison, eg the interest rate and the planning horizon. As regards the losses, the short planning horizon chosen for this comparison results in the saving due to GIS being underestimated.

When state-of-the-art AIS and GIS components are used, the cost of their maintenance and inspection will be a minimum. As the comparison shows, the maintenance costs have no impact on the variant ranking. The GIS variant exhibits the lower costs as it needs fewer inspections per switchbay (GIS once every 8 years, AIS once every 5 years), of which it also has fewer.

The final factor in the comparison is the cost of supply interruptions, ie the costs at the load end resulting from interrupted service. Although it is the customer who foots the bill, these costs enable the non-reliability of the network to be defined in monetary terms.

Significant differences also exist between the 10-kV and the 20-kV MV supply. A 20-kV network can, roughly speaking, transfer twice as much power as a 10-kV network over the same cable cross-section. This either reduces the investment in primary equipment (due to the smaller number of MV cables) or leads to lower losses for the same cable cross-section.

This effect is relativized in actual planning. The maximum number of MV substations supplied by the same cable in high load density areas is limited not only by the ampacity of the feeder cables but also by the need to keep the number of customers affected by a single failure as low as possible. Another constraint is due to the open-loop topology: the MV substations must be assigned to two half-loops, each of which starts at the HV substation busbar and is linked to the
other via a disconnect point in the network.

The cost comparison of the GIS and the AIS variant in the case of the 20-kV network shows reduced differences in losses and in the investment in MV cable. However, the costs are still significantly (approx 4%) higher for the AIS variant.

The direct comparison of the 20-kV and 10-kV variants for similar HV technologies shows an advantage for the 20-kV solution. This result is plausible and in line with actual planning experience.

**Reliability of the AIS/GIS variants**

A reliable electric supply is especially important in urban networks where load densities are high and users are sensitive to interruptions. The outage and reclosure behaviour is an area in which there is a fundamental difference between the GIS/cable and the AIS/overhead line solutions, at least as far as the main power users are concerned.

110-kV cable faults are rare, being due in most cases to accidental damage during construction work. Since HV cables are buried deeper than MV cables, the latter, which are laid above them, give them a certain degree of ‘protection’. If the HV cable itself is not sufficiently robust (eg, protected by a surrounding steel tube, as in the case of pipeline compression cable) concrete ducts can be used to provide the necessary shielding. This minimizes the failure rate even in supply regions in which large-scale construction work is carried out.

Besides their cost, the main drawback of HV cables is the long time needed for their repair, as HV cables are typically spliced by the supplier’s staff.

The characteristic behaviour of overhead lines is somewhat different to that of cables. Overhead lines exhibit high outage rates but short outage times. To keep overhead line systems compact, parallel circuits are run on the same pylons. As mentioned before, a single event can therefore lead to common mode failures in which several circuits are tripped. This aspect is important and has to be considered in every reliability comparison.

Table 1 shows the values used in the reliability calculations for the HV lines/}

![Graph showing interruption frequencies (IF) at the MV busbars of the HV substation]

<table>
<thead>
<tr>
<th>Substations</th>
<th>Interruption frequencies (IF) at the MV busbars of the HV substation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1, 2, 3, 4</td>
<td>Transformer substations 1, 2, 3, 4</td>
</tr>
<tr>
<td>SS1, 2</td>
<td>Satellite stations 1, 2</td>
</tr>
</tbody>
</table>

Table 1 shows the values used in the reliability calculations for the HV lines/cables. The high value for the outage rate is a pessimistic estimate in which the majority of the faults are assumed to be caused by external cable damage. A reliability calculation was performed to quantify the differences between the 10-kV variants of the AIS/GIS concepts. The calculation simulates relevant component failure modes and evaluates and quantifies the consequences for the customers. The component behaviour is derived from statistics about failures in the past.

**Table 1: Reliability data for cables and overhead lines (110 kV)**

<table>
<thead>
<tr>
<th></th>
<th>Outage rate per year and 100 km</th>
<th>Repair duration (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhead HV line</td>
<td></td>
<td></td>
</tr>
<tr>
<td>short (1 circuit)</td>
<td>0.21</td>
<td>1</td>
</tr>
<tr>
<td>long (1 circuit)</td>
<td>0.04</td>
<td>20.5</td>
</tr>
<tr>
<td>Overhead HV line</td>
<td>0.15</td>
<td>2.7</td>
</tr>
<tr>
<td>(common mode)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV cables</td>
<td></td>
<td></td>
</tr>
<tr>
<td>short</td>
<td>0.35</td>
<td>3.4</td>
</tr>
<tr>
<td>long</td>
<td>0.35</td>
<td>298</td>
</tr>
</tbody>
</table>

1) Independent, stochastic outages
The results of the calculation are shown in 10. It is evident that the interruption rates are much lower for the GIS/cable variant, although high failure rates for the HV cables have been assumed. The effect on the reliability is felt at the MV busbars of the HV transformer.

The values for GIS are of the order of 0.01 per year, i.e. one interruption every 100 years. The interruption frequencies for the AIS substations TS1 and TS4 are of the same magnitude, but TS3 and especially TS2 are more frequently affected (by a factor of 3 to 4). The reason is the loop-in via a double overhead line, which has been assumed in both cases, and in addition for TS2 the double-T connection to the surrounding ring (also a double overhead line).

The values for the satellite stations receiving power from TS1 and TS2 are the same as for the MV busbars of the HV transformer substations. This is plausible because of the selective protection provided for the parallel transmission cables between the transformer substations and the satellite stations; neither a single nor multiple cable failure will affect the satellite supply as long as the protection devices work correctly.

As shown in 10, there are no significant differences between the AIS and the GIS variant within the MV network.

The reason lies in the radial operation of the MV loops. Every fault leads to the attached feeder tripping and interrupting the supply to all customers in the same half-loop. This interruption of service is usually ended by (manual or remotely controlled) switching. The large number of events in the MV network compared with those in the 110-kV system dictates the interruption behaviour and ensures comparative reliability at all customer nodes. This effect is underscores by the comparable interruption costs for AIS and GIS.

In cases where a special-tariff customer is connected to the HV transformer substation via parallel cables, the reliability of the HV substation is passed on to the customer, who also benefits in this way from the GIS solution.

Conclusions

Although the GIS solution appears initially to be the more costly, its flexibility allows the HV transformer substations to be sited in optimum locations. The number of injections from the HV system can be optimized and the transmission load of the MV network reduced. This leads to a significant saving in investment as well as operating costs which more than compensates for the additional cost of the GIS and HV cables.

Another advantage of the GIS/cable combination is that it offers better reliability than the AIS/overhead line solution. Major customers linked to the HV substation via parallel MV cables also experience this in everyday operation. And being inherent advantages of the GIS/cable variant, these benefits cost the network operator nothing.

GIS technology also offers further benefits which are harder to quantify but which can be decisive for the realization of a project. One example is the option of complete integration of a GIS substation in an existing building when no extra site area is available. Summing up, GIS is a cost-efficient, flexible and reliable solution for supply systems in regions with high load densities.

Authors

Werner Zimmermann
André Osterholt
Dr. Jürgen Backes
ABB Calor Emag Schaltanlagen AG
Käfertaler Str. 250
D-68167 Mannheim
Germany
E-mail: werner.zimmermann@deace.mail.abb.de
andre.osterholt@deace.mail.abb.de
juergen.backes@deace.mail.abb.de