RELIABILITY-ASSESSMENT AS BASIS FOR NEW TRANSFORMER SUBSTATION CONCEPTS

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RELIABILITY-ASSESSMENT AS BASIS FOR NEW TRANSFORMER SUBSTATION CONCEPTS

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The presented study compares the reliability of typical configurations of transformer substations (S/S) for subtransmission networks (72.5 – 170 kV). The study is based on comprehensive probabilistic reliability calculations carried out by ABB’s Electric System Consulting. The motivation for the study was to reduce the large variety of configurations of subtransmission transformer S/S by defining typical functional requirements and by finding configurations which fulfill these functional requirements at an economical and technical optimum. The outcome of this study was used for defining basic configurations within ABB’s new transformer S/S concept PS-1. Within this contribution especially the results for gas-insulated (GIS) HV-switchgear are discussed.

The considered transformer S/S are connected to the subtransmission network via one or two circuits. They fulfill mainly local supply functions. They serve as infeed to the distribution level and have typically one or two HV/MV transformers with rated power from 10 MVA up to 80 MVA.

Depending on their network connection transformer S/S provide only a supply-function (single-circuit and double-circuit radial connection) or a supply- and a transfer-function (loop connection). The transformer S/S (un)reliability is quantified by the interruption frequency and the unavailability of these functions.

As a conclusion from the reliability assessment three transformer S/S configurations H1, H3L and P4 are recommended for standardized GIS transformer S/S.

1 TYPICAL SUBTRANSFORMATION CONFIGURATIONS

The subtransmission level covers network voltages from 72,5 kV – 170 kV (highest voltage for equipment acc. to IEC38). The operation philosophy of subtransmission networks influences the design of its S/S. In principle subtransmission S/S can be divided into two main classes [1].

- **Main S/S** have an infeed from the transmission network via one or more transformers or they have at least multiple, i.e. via more than two connections to the subtransmission network.

- **Transformer S/S** are connected to the subtransmission network at high voltage (HV) via one or two circuits. They fulfill mainly local supply functions. They serve as infeed to the distribution level at medium voltage (MV) and have typically one or two HV/MV transformers with rated power from 10 MVA up to 80 MVA. The rated power per transformer is mainly determined by the load demand, the redundancy concept and the short-circuit-strength of the MV-switchgear.

All further considerations within this contribution are only dealing with transformer S/S.

Looking at typical subtransmission systems, it can be stated, that in contrast to main S/S transformer S/S are not building up the subtransmission network’s structure.

The design of the transformer S/S’s network connection depends on the configuration of the subtransmission system. Figure 1.1 shows typical network connections of transformer S/S.

- **Single-circuit and double-circuit radial** connections are built as direct connections with a main S/S or as T/double-T-connections with overhead lines passing by close to the transformer S/S. In these cases there is no load transfer via the transformer S/S required.

- **Loop** connections are built as connections between several (at least two) main or transformer S/S. In case of a loop connection there is a load transfer via the transformer S/S required.
The reliability of a transformer S/S describes the ability to provide a required function during a defined time interval under specified conditions. The reliability of a transformer S/S can thus only be quantified, if its functions are defined. Based on the considerations made above each transformer S/S may provide two basic functions (see figure 1.2). These are:

- **The supply-function**, i.e. the function to supply the load connected to the MV-busbar(s).
- **The transfer-function**, i.e. the function to keep up a connection within the subtransmission network and to transfer load via this transfer path.

The conditions under which these functions have to be provided are to keep the voltages within a specified range and to keep the line- and transformer-loads within the respective thermal capacities. All transformer S/S have a supply-function, but only the loop-connected ones have to provide a transfer-function.

## 2 METHODS AND MODELS

The quantification of a transformer S/S’s reliability requires the application of probabilistic methods instead of a qualitative assessment, e.g. on the basis of the (n-1)-criterion. ABB’s network calculation software CALPOS® provides a calculation module for quantitative reliability assessment. The calculation method is internationally accepted and was verified in several national and international studies [2]. It takes into account the failure behaviour of the equipment. All relevant failure scenarios are systematically analysed. In addition to independent single failures, types of failures that proved in the past to be a significant factor in disturbances are also analysed. In contrast to the qualitative approach of the (n-1)-criterion, this allows further statements that differentiate between transformer S/S configurations that are evaluated equally on the basis of the (n-1)-criterion.

In the presented study the reliability is quantified by the following indices:

- **The interruption frequency** \( f_{int} \) (in 1/a) of a function gives the expected number of interruptions of that specific function per year. It says nothing about the expected duration of the interruptions.
- **The unavailability** \( q_{int} \) (in min/a) of a function represents the cumulative amount of time that a specific function experiences an interruption in a one-year period. The unavailability is calculated by multiplying the interruption frequency with the mean duration of interruptions, i.e. long interruptions contribute more to this index than short interruptions.

Interruptions of a transformer S/S’s function may have different reasons. Mainly they can be divided into interruptions due to component failures - **stochastic unavailability** -, and interruptions due to scheduled maintenance - **determined unavailability** -. Their effect on the loads (supply-function) as well as on the subtransmission network (transfer-function) are quite different. Component failures occur unforeseen and lead to tripping of the protection system. If they lead to interruptions, these can be ended either after system re-configuration (switch-
ing measures of the system management) or after repair of the faulty equipment. In contrast to this, scheduled maintenance in general does not lead to any interruption. In case of an interruption, it will be planned so that it’s effect will be minimised (e.g. during a low load period) and it will be co-ordinated within the subtransmission system. Looking at the financial damage due to interruptions, this means that determined unavailability will only cause very low interruption cost, if any.

As reliability is defined as the ability to provide a required function during a defined time interval under specified conditions, it is of decisive importance to define a suitable S/S model and preconditions for the reliability assessment. In the presented study a S/S model with the following preconditions was defined:

- The surrounding subtransmission network except the infeeding lines and the MV-switchgear do not fail.
- The HV-switchgear as well as the infeeding lines and the transformers fail with their characteristic outage frequency and repair duration. These reliability data are given in the appendix.
- The line and transformer capacity are redundant.
- The MV-switchgear is designed with two busbar sections and a normally open operated bus-tie, so that in case of an interruption of one busbar, the connected loads are resupplied by closing the bus-tie.
- The bus-tie on the HV-side is operated normally open for double-circuit radial connected transformer S/S. It is operated normally closed for loop connected transformer S/S.
- The MV-network is represented by loads connected directly to the busbars of the MV-switchgear.
- The supply-function is interrupted, if one of the loads connected to the MV-busbars is interrupted.
- The transfer-function is interrupted, if one of the lines, one of the busbar sections or the bus-tie is disconnected.
- The transformer S/S is remote-controlled. The MTTS (mean time to switch) is 1 hour. The MTTS includes the whole time period from circuit breaker tripping until the respective switching measures to resupply the connected loads or the transfer-function are finished. The MV bus-tie is operated automatically.

3 TYPICAL GIS TRANSFORMER S/S

Figure 3.1 gives an overview on typical GIS subtransmission transformer S/S.

![Figure 3.1: GIS transformer S/S configurations](image)

The H-configurations (H1..H5) differ from each other by the number and the position of the circuit-breakers (L=line-side, T=transformer-side) and the design of the bus-tie. ST5 is a single-busbar configuration with a transfer busbar and D5 a double busbar configuration each of them with 5 circuit-breakers. P4 is a polygon configuration with 4 circuit-breakers.
Single failures of lines and transformers shall not lead to interruptions of the whole transformer S/S. Therefore the configurations 2xH1, H2T, H2L and H4 are only suitable for double-circuit radial connections. The other configurations, H3T, H3L, H4, H5, ST5, D5 and P4 are also suitable for loop connections.

3.1 GIS TRANSFORMER S/S FOR DOUBLE-CIRCUIT RADIAL CONNECTIONS

The common characteristics for double-circuit radial connected transformer S/S are

- There is no transfer-function required.
- The HV-bus-tie is designed with two disconnector switches, i.e. each of them can be maintained without taking both busbar sections out of service.
- The HV-bus-tie is operated normally open.
- Single line and transformer failures interrupt the supply-function until the MV-bus-tie is closed; the HV-bus-tie provides additional flexibility (only H2T, H2L, H4).
- All components can be maintained without an interruption of the supply-function.

2 x H1 is the most simple configuration. The only way to resupply the connected loads after a switchgear-, transformer- or line-failure is to close the MV bus-tie.

H2T is a very simple H-configuration. The two circuit breakers are installed on the transformer side. Line failures will also interrupt the connected transformer. Transformer failures do not affect the adjoining lines and are cleared selectively. However, line and transformer failures interrupt the supply-function.

Also H2L is a very simple H-configuration. In contrast to H2T the two circuit breakers are installed on the line side. Transformer failures will also interrupt the connected line. Line failures do not affect the adjoining transformer and are cleared selectively. As for H2T both, line and transformer failures interrupt the supply-function.

H4 is the most complex H-configuration for double circuit radial connection. It combines the features of H2T and H2L. Neither line nor transformer failures affect the connected transformer or line but in any case interrupt the supply-function.

3.2 GIS TRANSFORMER S/S FOR LOOP CONNECTIONS

The common characteristics for loop connected transformer S/S are

- There is a transfer-function required.
- The bus-tie is designed with a circuit-breaker and two disconnector switches, i.e. the circuit-breaker can be maintained without taking both busbar(s / sections) out of service.
- The bus-tie (except ST5) is operated normally closed. In case of any busbar related failures it separates the two busbar(s / sections) and all loads connected to the faulty busbar (section) can be resupplied.
- Single line failures do not interrupt the supply-function (except H3T).
- Transformer failures interrupt the supply-function until the MV-bus-tie is closed.
- All components can be maintained without an interruption of the supply-function.
- Maintenance leads to unavailability of the transfer-function.

H3T is a very simple H-configuration. The two circuit breakers are installed on the transformer side. In contrast to all other loop configurations line failures will also interrupt the connected transformer and the bus-tie, i.e. the supply-function and the transfer-function will be interrupted. Transformer failures do not affect the adjoining lines and are cleared selectively. However, transformer failures interrupt the supply-function (but not the transfer-function). The transfer path provides no redundancy, i.e. any failure as well as any maintenance in the transfer-path lead inevitably to interruptions of the transfer-function.

Also H3L is a very simple H-configuration. In contrast to H3T the two circuit breakers are installed on the line side. Transformer failures will interrupt the connected line and the bus-tie, i.e. the supply-function and the transfer-function will be interrupted. Line failures do not affect the adjoining transformer and are cleared selectively, i.e. the supply-function will not be interrupted but the transfer-function. As for the H3T configuration, the transfer path provides no redundancy. Due to the limited switching capacity of the transformer related disconnectors, re-energising of the transformer after repair or maintenance requires switching of the related line circuit-breaker and the HV bus-tie.

H5 is the most complex H-configuration. It combines the features of H3T and H3L. Neither line nor transformer failures affect the connected transformer or line. Thus line failures will only interrupt the transfer-function and
transformer failures will only interrupt the supply-function. The HV bus-tie provides additional flexibility. As for H3T and H3L the transfer path is not redundant. 

ST5 as well as the following D5 represent the more complex and traditional configurations. Neither line nor transformer failures affect each other. Due to the single-busbar design (the second busbar is only a transfer-busbar) both lines as well as both transformers are connected to the busbar, i.e. in cases of any busbar related failure all feeders will trip. Line failures will only interrupt the transfer-function and transformer failures will only interrupt the supply-function. In contrast to all previous configurations ST5 provides redundancy in the transfer path. However maintenance of the transfer disconnector switches also leads inevitably to interruptions of the transfer-function. 

D5 represents the traditional configuration. Neither line nor transformer failures affect each other. The double-busbar design allows to supply each transformer by each of the incoming lines. Normally each of the transformers and each line will be connected to one busbar respectively. Line failures will only interrupt the transfer-function and transformer failures will only interrupt the supply-function. Also D5 partly provides redundancy in the transfer path (see ST5). Partly, because failures or maintenance of the circuit breakers or of the line disconnectors will interrupt the transfer-function. 

P4 is the configuration with the most inherent redundancies. All circuit-breakers are normally closed. Neither line nor transformer failures affect each other. Line failures will only interrupt the transfer-function and transformer failures will only interrupt the supply-function. The polygon configuration provides additional flexibility. Only failures or maintenance of the line disconnector switches will inevitably lead to transfer interruptions. 

4 RELIABILITY COMPARISON

4.1 GIS DOUBLE-CIRCUIT RADIAL CONNECTION

As already explained in section 3, all transformer S/S for double-circuit radial connections have one thing in common: single failures of the infeeding lines, the transformers and also the switchgear lead to an interruption of the supply-function. All these failures end after closing the MV-bus-tie. Thus comparing the stochastic interruption frequency / unavailability of the supply-function, shown in the diagrams 4.1 and 4.2 one gets a at the same time surprising and reasonable result: the most simple configuration 2 x H1 is the most reliable one.

![Stochastic interruption frequency and unavailability of the supply-function of double-circuit radial connected transformer S/S](image)

Figure 4.1 and 4.2: Stochastic interruption frequency and unavailability of the supply-function of double-circuit radial connected transformer S/S

Fewer components mean fewer failures. At the same time the additional components do only provide additional reconfiguration options for double failures. As double failures are extremely seldom, it is reasonable that additional equipment does not lead to an increased over-all reliability, as the results show clearly. 

As single line failures lead to supply interruptions, the absolute values of the interruption frequency and the unavailability extremely depend on the specific network configuration, especially the length of the connected lines. 

4.2 GIS LOOP CONNECTION

One main difference between loop connected transformer S/S and radial connected transformer S/S is, that single line failures do not lead to interruptions of the supply-function for one exception: H3T, because for this configuration line failures will interrupt the connected transformer and the bus-tie. Comparing the stochastic interrup-
tion frequency/unavailability of the supply-function, shown in figure 4.3 and 4.4 the following conclusions can be made:

- As any busbar related failure trips all feeders, the configuration ST5 has the supply-function with the lowest reliability of the investigated configurations.
- Although the interruption frequency of H3T is even higher than for ST5, the unavailability of H3L, H3T, H5 and D5 is more or less of the same order. In comparison with the reliability indices for D5, which is an accepted standard, these configurations have a supply-function with standard reliability.
- For P4 besides of transformer failures only single failures of transformer related disconnectors lead to supply interruptions. Compared with all other configurations P4 has the supply-function with the highest reliability of the configurations under investigation.

For loop connected transformer S/S also the transfer-function has to be considered. D5, ST5 and P4 provide redundancy in the transfer-path whereas it is non-redundant for all other configurations. This has no significant effect on the stochastic interruption frequency but on the unavailability of the transfer-function as shown in figures 4.5 and 4.6.

The following conclusions can be made:

- The interruption frequency of the transfer-function of all configurations is more or less of the same order and depends very much on the investigated network. Looking on the unavailability of the transfer-function it is obvious, that it is of the same order for H3L and H5 as well as for H3T, ST5, D5 and P4.
- The configurations H3L and H5 have a transfer-function with lower reliability.
- The configurations H3T, ST5, D5 and P4 have a transfer-function with higher reliability.
Furthermore all loop connected configurations have one thing in common: they do not provide a (n-1)-secure transfer-path. Table 4.1 shows the determined unavailability of the transfer-function.

<table>
<thead>
<tr>
<th>H3T</th>
<th>H3L</th>
<th>H5</th>
<th>ST5</th>
<th>D5</th>
<th>P4</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.2</td>
<td>37.6</td>
<td>37.6</td>
<td>19.2</td>
<td>27.2</td>
<td>19.2</td>
</tr>
</tbody>
</table>

Table 4.1: Determined unavailability of the transfer-function for loop-connected transformer S/S

It is obvious that H3L and H5 cause the same determined unavailability of the transfer-function which is higher than for H3T, D5. H3T and D5 have a transfer-function, which also has more or less an equal determined unavailability. The lowest determined unavailability is provided by ST5 and P4.

Looking quantitatively at the determined and stochastic unavailability of the transfer function it can be deduced that for a reliable operation of the subtransmission network a sufficient redundancy within this system has to be provided. In this case the selection of the transformer S/S configuration will mainly be guided by the choice of the supply function reliability.

### 4.3 CONCLUSIONS

Finally, taking the equipment cost into account, three configurations are recommended for standardised GIS transformer S/S:

- 2 x H1 for double-circuit radial connections
- H3L for loop connections with low requirements on the availability of the transfer-function
- P4 for loop connections with high requirements on the availability of the transfer-function

### 5 THE SUBSTATION CONCEPT PS-1

The results presented above were used as a basis when developing ABB’s new S/S concept PS-1 (Productified Substation-1). The PS-1 project was set up in order to meet the changing requirements of the markets for electrical energy due to liberalisation. Because of the increasing cost pressure on utilities in deregulated markets one of the basic requirements on S/S today is reduced investment costs. In addition fast delivery times and reduced efforts on the utility side in handling S/S projects are to be realised. All this of course keeping the same reliable functionality of the S/S as before.

![Basic technical functionality of a PS-1 S/S](image)

Figure 5.1: Basic technical functionality of a PS-1 S/S

The approach of PS-1 for meeting these requirements was to develop a set of completely pre-designed S/S and to optimise the whole logistic process around a S/S project thus standardising the hardware of the S/S and the respective processes. As the number of pre-designed S/S has to be limited when creating a standard, a selection has to be made with regard to the field of application (e.g. number of incoming lines, AIS/GIS solutions, voltage levels etc.). The basic functionality of the PS-1 S/S portfolio is given in Figure 5.1.
In order to further select S/S configurations the function of S/S were evaluated in more detail. This was done for e.g. the supply-function by means of the reliability assessment. The S/S configuration recommended in section 4.3 therefore were chosen as the basic layouts for PS-1 (GIS). Results for AIS solutions are not discussed within this contribution. A typical layout of a PS-1 S/S with a H3L GIS configuration is shown in Figure 5.2.

Figure 5.2: Pre-designed PS-1 S/S – H3L with EXK-0 GIS for 123kV

Due to the comprehensive pre-design, pre-fabrication, and pre-documentation as well as the refined and standardised logistic process the typical cycle time of a PS-1 S/S project can be cut in half compared to traditional S/S projects. The reduction in costs because of the standardisation is also significant.

6 REFERENCES


[2] Paechnatz; Röstel; WellBlow; Weber; Nippert; Luther; Neumann; Haubrich; Clemens; Koglin; Schwan; Zimmermann; Zdrallek; Reinisch; Hartmann: Zur Aussagekraft der Ergebnisse von Zuverlässigkeitserhebungen (About the significance of reliability calculation results), Elektrizitätswirtschaft 16/99 pages 30-33


7 APENDIX

Component reliability data [1][3][4][5]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Outage frequency #/yr</th>
<th>Repair duration h</th>
<th>Maintenance frequency #/yr</th>
<th>Maintenance duration h</th>
<th>Maintenance interruption h</th>
<th>Protection failure %</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV GIS busbar (per bay)</td>
<td>0.00036</td>
<td>72</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>HV GIS circuit breaker</td>
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<td>72</td>
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<td>60</td>
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<tr>
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<td>-</td>
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<td>HV/MV transformer</td>
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</tr>
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<td>1.0</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HV line long</td>
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<td>20.5</td>
<td>-</td>
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