RELIABILITY OF AIR INSULATED SUBSTATIONS AS ADDITIONAL INFORMATION FOR PRIORITY DRIVEN MAINTENANCE

C. Hille[1*], S. Federlein[1], A.Schnettler[1] and B. Rusek[2]
[1]Institute for High Voltage Technology, RWTH Aachen University, Germany
[2]AMPRION GmbH, Germany
*Email: hille@ifht.rwth-aachen.de

Abstract: Increased cost pressure leads to reassessment of maintenance strategies for electrical power systems worldwide. In the past, fixed maintenance cycles or time intervals based on the equipment's age were very common. Future strategies have to take the influence on power system quality and thus the non-availability of assets into account. This requires a type-specific analysis of failure rates, repair-time and substation configuration. This paper presents a detailed investigation of non-availabilities of single primary assets based on real failure data. By application of a modified minimal cut-set calculation, the reliability of certain bays and its sensitivity on maintenance intervals depending on the substation setup are shown.

1 INTRODUCTION

Liberalization, unbundling as well as regulatory authorities have a great impact on asset management decisions. Power systems have to be operated at lower costs, but with constant or even higher quality. This requires concepts to increase the efficiency of all processes within companies.

The fastest way to reduce costs is usually reduced maintenance effort. This could result in more frequent repairs and a loss of supply quality.

Transmission systems are meshed and contain redundancy to ensure a high degree of availability. This safety margin could result in the idea, that a certain increase of equipment failure rates can be tolerated for these grids. It neglects on the other hand, that the impact of these failures could be state- or country-wide outages. As the security of supply ensures economic growth and further technical development for industrial countries, latter is not acceptable.

Thus, knowledge of equipment's behaviour and its impact on non-availability (NA) of bays in substations is inevitable for the assessment of asset management decisions. There is no reliability definition for transmission systems, as direction of load flow and the number of customers varies over time in meshed grids. But a minimal cut-set method offers the possibility to analyze the failure probability of bays based on type-specific failure rates. It additionally enables more precise reliability calculations of entire power systems and supports a system view on failure rates of single grid components.

2 CALCULATION OF FAILURE RATES

The Institute for High Voltage Technology (IFHT) holds a database with information of a large European grid operator. It contains data of about 45.000 high and extra high voltage assets (circuit breakers, disconnectors, instrument transformers and surge arresters) with 8.000 digitalized maintenance protocols and failure data of about 830.000 asset service years.

This data is used to calculate type specific failure rates for all relevant assets.

$$\lambda(t) = \frac{F_t}{A_t} \tag{1}$$

where: λ = failure rate (1/a)
F_t= Number of failures in year t
A_t= Number of assets run through year t
t = year of interest

All failures addressed in this paper are major failures and lead to a direct disconnection and repair of the corresponding component. Components are analysed as three phase units. This means e.g. one 420 kV circuit-breaker represent three single phase ones.

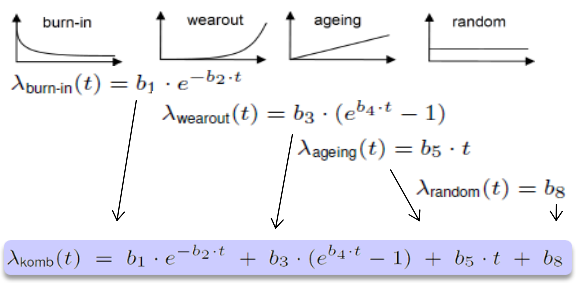

Figure 1: Model functions for regression analysis [1]

Final curves are obtained by regression analysis with 4 defined model functions using the Levenberg-Marquard algorithm for error minimization (see [1],[2]). Fig.1 illustrates this approach.

Application of this method to real data provides type specific failure rates. The results are presented in fig. 2 for different types of 123 kV circuit breakers as well as failure rates for the entire group of puffer type and selfblast circuit breakers. Dotted lines represent estimations for future development.

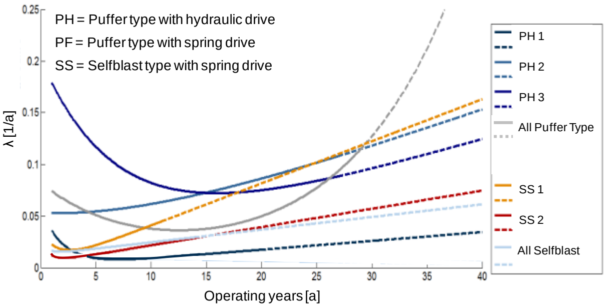

Figure 2: Failure rates of 123kV circuit breakers

For the analysis of substations it is necessary to investigate the behaviour of several groups of primary assets. Fig. 3 illustrates theses results for 245 kV circuit breakers, disconnectors and instrument transformers.

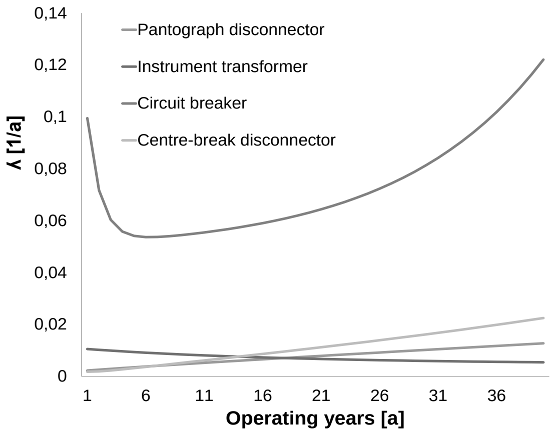

Figure 3: Failure rates of 245 kV primary assets

It is obvious, that failure rate curve-forms depend on the complexity of equipment. Typical forms are illustrated in fig. 4. Exponential growth of failure rates with increased aged can only be found for center-break disconnectors and circuit breakers, equipment with mechanical parts and wear out. A burn-in indicates teething problems caused by complex technology and in most cases electronic control. Instrument transformers have a decreasing failure rate. This is due to the fact, that failures of older transformers have not been recorded in total as some failures lead to a replacement. In this case only the replacement information was stored in the database.

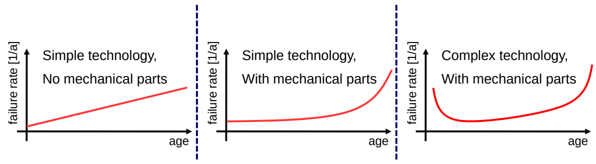

Figure 4: Typical failure rates depending on the complexity of assets

Knowing type specific failure rates, the expected value of failures and consequently the number of repairs for each substation can be calculated year wise. This enables an estimation of future costs and thus supports end-of-life decisions.

3 DERIVATION OF EQUIPMENT NON-AVAILABILITY

Substation or bay availability is important for transmission systems as some failure combinations can lead to countrywide blackouts. The (n-1)-criteria of course ensures continuous supply even after failure of one or even more grid components, but increasing NA result in higher risk for simultaneous failures.

Detailed information about all occurred failures and the equipment's time-to-repair (TTR) enables a derivation of equipment NA. The method is divided into three steps:

Step 1: Assigning TTR to each failure

All failures are recorded and automatically grouped into categories with special failure codes. A lookup table assigns TTR to these failure codes (fig. 5). The content of the lookup table was created by repair time measurements and know-how of experienced service personnel. It can differ between companies depending on repair strategies and distances to substations.

Database

Euqipment ID	Operating year	Failure code
1PH1a342	17	A3082
1PF1b561	22	C7281
2SS2a263	8	B8231
4PH2a837	14	A1831
1PH1b623	15	B2192
…	…	…

Lookup table

Failure code	TTR (h)
A0001	2
A0002	4
A0003	8
A0004	24
A0005	2
…	…

Figure 5: Assigning TTR to failures by lookup table

Step 2: Summation of all TTR in an operating year

All occurred TTR were summed up year wise. The result is a type specific total TTR per operating year.

Step 3: Calculation of average NA per operating year

After step two, the total TTR per asset and operating year is known. In step three, these times are divided by all assets run through the according operating year.

Fig. 6 shows the resultant NA and the failure rate exemplarily by applying this method to two 420 kV puffer-type circuit breakers with hydraulic drive. Circuit breaker (CB) 1 has two switching chambers; CB 2 has four of them.

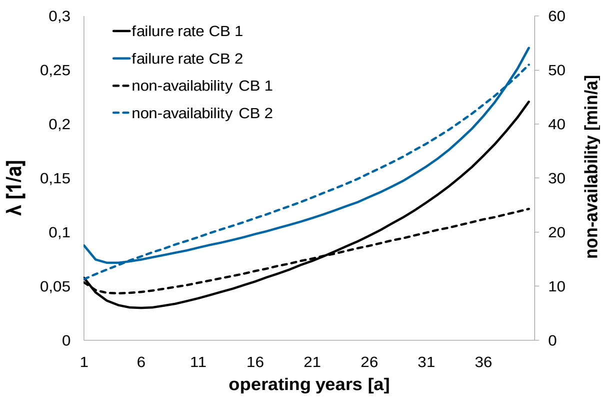

Figure 6: Failure rate and non-availability for two 420 kV circuit breaker types

The failure rates for both circuit breakers are typical bathtub curves. These curves have a very similar shape over the operating years. CB 2 has an approximately 80 % higher rate, due to more switching chambers and a consequently more complex drive and control mechanism.

Due to greater numbers and more complex failures with increased TTR, these curves develop into almost purely exponential functions for the NA. It is also determinable, that even though the failure rates are very similar in their shape, the NA are not. The more complex structure of a 4 chamber circuit breaker requires more and longer repair times with increased operating time.

Fig.7 illustrates the non-availability behaviour for four types of primary assets according to the failure rates of fig. 4. Circuit breakers have the longest non-availabilities per year. It reaches 50-60 min/a in the age of forty years.

The influence of instrument transformers is greater than expected after knowing the equipment failure rates. This is a result of longer repair times in case of internal failures. Disconnectors can very often be repaired on site while instrument transformers have to be taken to a workshop or to be replaced.

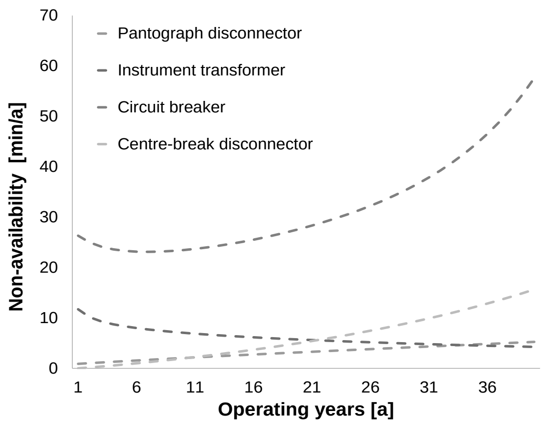

Figure 7: Non-availabilities (min/a) of primary assets

4 DERIVATION OF SUBSTATION NON-AVAILABILITY

After derivation of equipment NA the results are now used as input parameter for a bay non-availability calculation. Here, the following assumptions are made:

- failures of components are stochastically independent
- common mode failures are neglected (e.g. unwanted operation of protection system)
- (tele)controlled switching after failures is taken into account
- TTR starts directly after failure notification
- planned outages (maintenance) are neglected

Starting point for the analysis is a modelling of the substation topology. Single-line diagrams are transformed into k-partite graphs as shown in fig. 8.

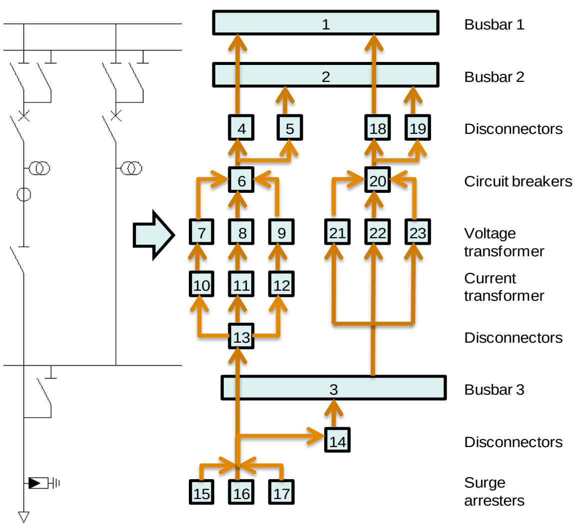

Figure 8: Transformation of single-line diagrams into vented graphs

Instrument transforms are modelled with a three phase layout due to that fact, that economic decisions sometimes lead to three or single phase setup of these elements. Failures of one of the three phase units of course lead to an outage of all phases. Busbar 3 is a transfer busbar.

Using the vented graph diagrams, adjacency matrixes are determined. After this, the area which has to be disconnected from mains in case of equipment failures is calculated for every failure mode as presented in fig. 9.

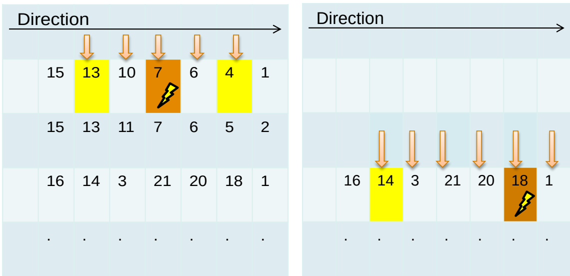

Figure 9: Determination of possible paths and associated disconnected areas in case of failures

Doing this, the adjacency matrix is reduced until minimal cut-sets are found. Minimal cut-sets represent the minimal combination of components that have to fail at the same time to disconnect two defined knots in a graph [3].

As switching status, direction and amplitude of currents in a substation are not definable for all time, the NA-calculations were done bay wise. The outcome is a bay-NA which is usable for system reliability calculations.

Each component can be in an operating and non-operating state (see fig. 10).

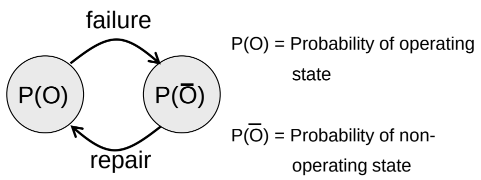

Figure 10: Operating states of grid-components

The probability of being in a non-operating state in one year for a certain type of component is:

$$P(\overline{O})_t = \frac{\sum_{i=0}^{I} TTR_i}{C_t \cdot a} \qquad (2)$$

Where: TTR_i = Time-to-repair for failure i (min)
i = failure number
I = total number of failures in year t
t = year of interest
C_t= Number of components run through year t
a = one year (525600 min)

The probability that all components in a minimal cut-set fail at the same time is:

$$P(MCS_n) = \prod_{k=1}^{K} P(\overline{O})_k \qquad (3)$$

Where: MCS_n = Minimal cut-set number n
k = Component number
K = Number of components in cut-set n

In the end, the non-availability of a certain bay in a substation is obtained by:

$$NA_{Bay} = \sum_{n=1}^{N} P(MCS_n) \cdot a \qquad (4)$$

Where: N = number of minimal cut-sets for the bay

4.1 Results

Fig. 11 shows the results of this calculation for a typical bay in a substation without transfer busbar (see fig. 8 without transfer busbar). To emulate changes due to modified maintenance strategies and to show sensitivities, failure rates of single assets have been doubled prior to calculation as assigned.
It can be seen, that the shape of the non-availability curves is dominated by the one of circuit breakers. These do also give most influence in case of modified failure rates.

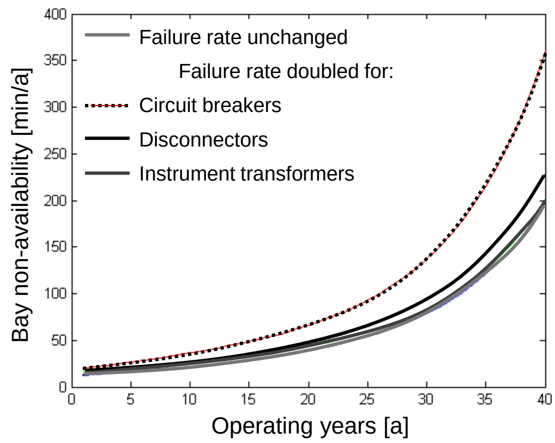

Figure 11: Bay non-availability, no transfer busbar

The result for a bay (according to fig. 8) with transfer busbar is shown in fig. 12.

In this case the NA is significantly lower because the additional transfer busbar can be used in case of failures to secure connectivity. Modifying the failure rates has no influence in many cases, only higher failure rates of disconnectors increase the NA.

Transfer busbars are expensive and not always necessary as the (n-1)-criteria already ensures a high availability in transmission systems. In case of possible quality regulations with monetary incentives to increase availabilities, these might be applied more often in the future.

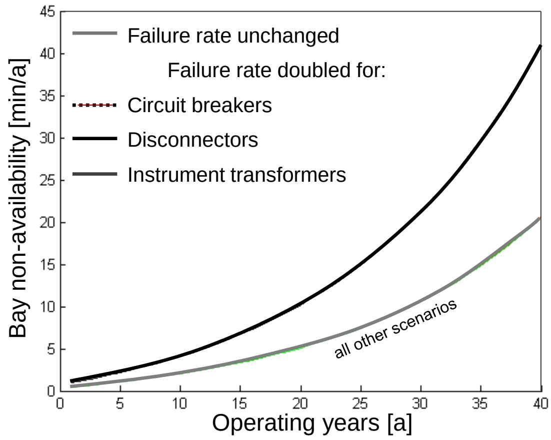

Figure 12: Bay non-availability, with transfer busbar

5 CONCLUSION AND OUTLOOK

This paper is based on equipment information stored in a large database at IFHT. The data was analysed and type specific failure rates were calculated.

Based on time measurements and additional heuristic knowledge, repair times were assigned to each recorded failure. It was shown, that this information can be used to derive the non-availability for many assets in substations. These times increase exponentially with higher operating years for most assets. Especially for circuit breakers this value reaches 50 min/a after forty years. Instrument transformers revealed slightly decreasing failure behaviour due to replacement strategies.

The observed curves were also used to calculate non-availabilities of bays in substations based on minimal cut-set analysis. The results were ten times higher reliabilities for bays in substations with transfer busbar. Simulated increased failure rates of single components also had a minor influence for these topologies.

The change of bay-NA depending on modified failure rates of single components for each substation design can be used as additional information for priority driven maintenance strategies for these assets.

ACKNOWLEDGMENTS

The authors wish to thank Alexander Parkitny and Pascal Koehn for their support.

REFERENCES

[1] S. Federlein: “Modelling the type specific failure occurrences of high voltage switching equipment”, Dissertation, RWTH Aachen University, Germany, 2010

[2] G. Balzer, C. Schorn: “Asset Management für Infrastrukturanlagen - Energie und Wasser“, ISBN 978-3-642-05391-7, Springer-Verlag Berlin Heidelberg, Germany, 2011

[3] A. A. Chowdhury, D.O. Koval: “Power Distribution System Reliability”, ISBN 978-0470-29228-0, Institute of Electrical and Electronics Engineers Inc., IEEE Press, USA, 2009