21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2013 Grid of the Future Symposium

Age-dependent & multi-load reliability analysis in transmission systems

M. FLECKENSTEIN*
TU Darmstadt
Germany

C. NEUMANN
TU Darmstadt
Germany

G. BALZER
TU Darmstadt
Germany

SUMMARY

Reliability calculations are a common part in risk analysis for transmission networks. Often only the extreme scenarios are considered to determine the maximum stress for the investigated grids. In the area of distribution, this is the right approach. For transmission networks, this is only partially valid. An evaluation of reliability calculations of a part of a German transmission network with different vertical load scenarios and power plant operational scheduling shows that the outage of assets in low- and medium-load situations have as well powerful effects on the system. In this paper it is illustrated that the risk assessment for the transmission system changed significantly in the consideration of all typical load conditions and age-dependent outage rates. The impairment of the availability of the supply of 110 kV network groups and the feed in of power plants varies with the different load situations. The determination of the importance of an individual asset for the reliability and availability of the network is highly dependent on the load situation and of its age. It is shown that this must be taken into account to make an exact risk analysis with a detail level to the individual asset. For the investigation ten different load flows are determined, which represent all typical load conditions of the network during a year. The assets of the examined transmission network are age-dependent and related to the real distribution in the network. It is shown in this paper that the results of calculations with standard values for the data reliability and extreme scenarios differ significantly from the exact calculations with age-dependence and multi load situations. The risk assessment which is needed for risk-based maintenance strategies (RBM) obtains from the standard calculations inaccurate or wrong statements. The developed RBM strategy would be incorrect and would reduce significantly the reliability and availability of the transmission network. The asset management would thus counter-productive change its maintenance.

KEYWORDS

RELIABLILITY, ASSET MANAGEMENT, RISK ANALYSIS

Marco.Fleckenstein@eev.tu-darmstadt.de

1. Introduction

Transmission System Operators (TSO) are faced with a manifold of new challenges. In 1998 the liberalization of the energy market in Europe has begun. The followed unbundling of the large electrical power supply companies in Germany into power generation, distribution and transmission has removed the territorial monopolies. All these businesses are now reliant to generate positive economic figures, as cross-subsidies are no longer allowed [1]. In the area of transmission systems it is a difficult task to achieve a positive financial result. The reach or continuing of the ultimate goal of high reliability and availability of energy supply is getting more complicated by these economic pressures. The network charges which are taken by the TSO are regulated by law and in addition, the shareholders are interested in a positive yield. The opportunities for increasing the revenues are very limited. The earnings can only be permanently enhanced by a reduction in operating costs. Maintenance of the assets absorbs a large proportion of these costs in a transmission network. Often, the change of the time-based maintenance (TBM) to the risk-based maintenance (RBM) is performed. Basis for the determinations of the new strategies are mainly the results of reliability calculations. Here, mainly the extreme scenarios, peak load or low load scenarios, are used for the calculations. In this paper it is shown that this approach cannot point out the risk assessment of the individual asset outage in the transmission network which is necessary for RBM strategies. With a database of ten different load flow scenarios, which represent all usual load situations during a year, reliability calculations were done which demonstrate that maximum asset outage impacts can occur during all load situations. Many maximum influences are held in the peak load scenario. But there are also asset outages which have their greatest impact on the transmission network in other load conditions. Their signification for the reliability and availability of the transmission system is wrong detected in many cases. So analyses and recommendations of these calculations to create a RBM of assets are significantly different to those basing only on the extreme scenarios. In this paper is shown that in the 380 kV level it is necessary to use all usual load conditions and age-dependent outage rates to determine the outage effects risk of the individual asset.

2. Materials and Methods

For the determination of the results, which are presented in this paper, a transmission network model has been used and reliability calculations were performed with different load situations and power plant scheduling. The model in this study is based on a part of the transmission system of a TSO in Germany which represents all typical transmission system parts e.g. rural and urban areas. It has been created with commercial network simulation software and includes the entire 380 kV, 220 kV voltage level and ends with the vertical feeding into the 110 kV network groups. These groups end with an aggregate load, which is supposed to represent the consumption of this area. In the reliability analysis, the outage of an asset is evaluated individually, e.g. was an overload or violation of voltage limits responsible for a load shedding [2]. The structure of the transmission network model is presented in the next three sub-sections.

2.1. The 380 kV transmission network

The highest voltage level in the created model is 380 kV. This level is the main part of the model. The risk determination is done for all assets in this voltage level. All types and quantities of the equipment in the 380 kV transmission network are:

- 145 bus bars
- 302 center break disconnectors
- 337 circuit breakers
- 30 generator units
- 4453 km overhead lines
- 952 pantograph disconnectors
- 103 power transformers

The structure of this voltage level in the model is very detailed. Overall it has 60 substations with different layouts, 23 power station connection points and ten connection points to neighboring TSOs. The structure of each substation is reproduced in detail, and is provided with the real switch settings in all ten load situations. The total transmission capacity of the ten connection points to other TSOs is around 29 GVA [3]. These coupling points have no further restriction except the transmission capacity of the transmission line. The voltage angles at the slack nodes, representing the neighboring transmission system, are set to zero, which is considered to be the ideal case. The various layouts of substations are important for the determination the importance of the individual asset. The overhead lines with a total length of 4453 km are reproduced exactly. Different types of overhead lines are used in the model [4].

The reliability characteristics that have been used for the calculations are from the VDN disturbance statistics and the age-dependent outage rates which bases on the VDN disturbance statistics combined with the age distribution are shown in Figure 1 [5]. The assets are divided in eight age groups. The age of the assets are based on data of a German TSO. An exception by the reliability data was made in case of the power plant connections up to the connecting substation. They are considered ideal because they are in the sphere of responsibility of the power plant operators and not of the transmission system operator.

VDN average outage rates

Element	Outage rate H in [1/a]	Outage duration T in [h]
Bus bar	0.00032	6.35
Center break disconnector	0.000513	67.63
Circuit breaker	0.001473	64.69
Overhead lines [a]	0.001562	5.34
Selector switch disconnector [b]	0	0
Power transformer	0.006411	65.99

a The outage rate for the overhead lines is related to 1 km.

b The outage rate of the selector switch disconnector is comprised within the outage rate of the bus bar.

Age-dependent outage rates

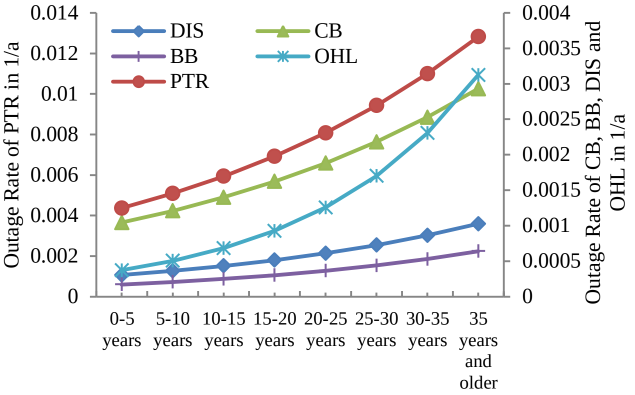


Figure 1: Comparison of average and age-dependent reliability values of assets.

2.2. The 220 kV transmission level

The 220 kV network is modeled schematically. Furthermore this voltage level is not considered with reliability data. But it is still needed for the simulation to determine realistic load flows in the 380 kV voltage level. Additionally, it is supplied by 31 power plant units with a total net output of 10 GW[7]. The 220 kV network has four connection points to other TSOs. The total transmission capacity of these couplings is around 4 GVA and has no restrictions except the transmission capacity of the transmission line [3]. A more detailed description of this voltage level can be omitted.

2.3. The 110 kV network groups

The 110 kV network groups are supplied through the 220 kV and 380 kV transmission levels and are directly fed by the power transformers. Power plants feeding directly into the 110 kV groups are not considered in that model. This voltage level has a total of 34 utility network groups and eight industrial network groups. Each of them has at least three to a maximum of eleven feeding power transformers. They are installed within one local area, but not within one substation. The load of each network group varies. The power factor is assumed to be equal to cos φ = 0.9 in all groups. All other details of the load scenarios are in the chapter power plants and load scenarios.

2.4. Power plants and load scenarios

Totally 61 power plant units are considered in the transmission system model. Different types of power plants are implemented and their individual behaviors are part of the reliability calculations. The gross output of all power plant units is 30.16 GW [7]. The values thereof, which are used in the model, can be found in Table I.

Table I: Key values of the power plants [8][9][10][11].

Type of power plant	Load gradients in % per minute	Share of auxiliary power in %	Number of power plant units	Installed gross power in MW
Hard coal	2 -4	7 – 10	18	10038
Lignite	1.5 – 2.5	10 - 16	27	8599
Gas turbine	25	2 - 4	1	112
Combined cycle	5	4 - 6	9	6286
Nuclear	10	4 - 5	3	3925
Pump storage	100	8.5	1	1096

The behavior of the power plants during an outage is considered. Therefore, different power gradients of the various types of power plants and the share of auxiliary power are taken into account. The priority of dispatch *K* specifies the order in which the power plants must participate in the outage clearing. The greater the number, the later position this type of power plant must take part on that task.

As the basis for the reliability and availability calculations ten representative load conditions of the network have been identified. The scenarios were created from the analysis of the sorted annual load and production curves of the investigated transmission system. Figure 2 shows the summed power fed into the 110 kV network groups and the accumulated production in the whole transmission network area during the ten load scenarios. The peak load scenario is labeled with the number 1. The low-load scenario has the number 10. This notation of the scenarios will be kept in the rest of the paper. In the area of this TSO the feed in is at all load scenarios higher than the requested power consumption of the 110 kV network groups. The surplus is transferred to the directly connected neighboring transmission networks. The power plant planning is done according to the typical operating hours of each type of power plant. The lignite fired power plants are at all times with the entire power in the transmission system. Other types of power plants, as shown in Figure 2, such as gas power plants significantly reduce the supply at low load.

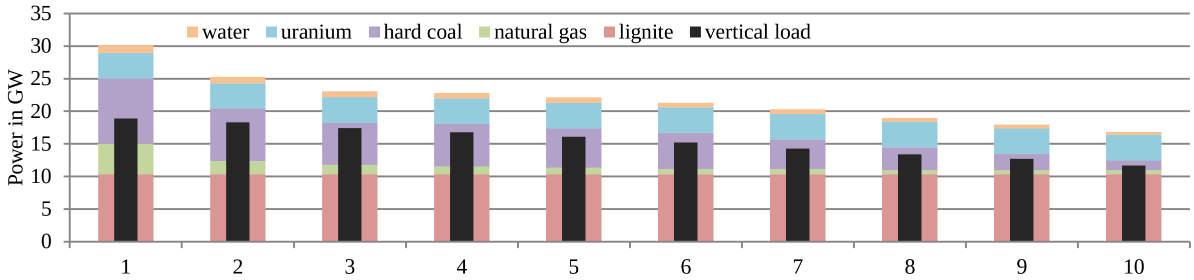


Figure 2: Different load and production scenario *k* of the transmission system.

Part of the gas turbine power plants can remain on the network. These are operated with blast furnace gas, which is subject to the Renewable Energy Act (EEG) in Germany, and therefore has priority [12].

For these ten load conditions of the transmission network reliability calculations are performed. For the outage of each asset in the 380kV level, except for the power plant connections, the effects in all scenarios are determined. These figures and their evaluations and comparison to the standard risk assessment are collected in the chapter results.

3. Results

The evaluation of the results is sorted into two parts. The impact on the delivery into the 110 kV network groups as well as on the power plant supply is considered. The analysis of the delivery into the 110 kV network groups summarizes the non-delivered energy caused by single outages of all assets in the 380 kV transmission system. This does not necessarily mean that it comes to load shedding in the underlying 110 kV network groups, but only that this transmission power is not supplied from the overlaid transmission network. Power plants that feed directly into this voltage level in many cases offset this shortfall. Nevertheless, it must be noted that the transmission network cannot fulfill its task and thus experiences a loss of network charges. The analysis of non-supplied energy includes the results of non-feed in power plant energy caused by the single major outages. For the clear presentation of the results four key figures are used. The outage rates H_C, equation 1, and H_P, equation 2, summarize all individual outage rates of assets, which cause non-delivered energy to the network groups (H_C) and non-supplied energy of the power plants (H_P).

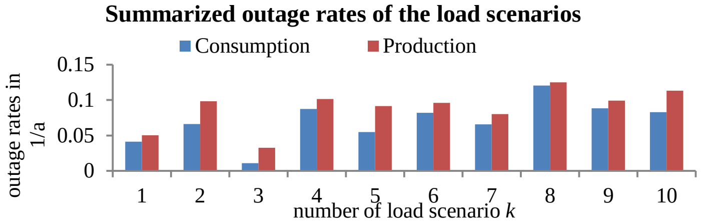
$$H_C = \sum_{n=1}^{m} H_n \cdot \Theta\left(W_{C,n}\right) \qquad (1)$$

$$H_P = \sum_{n=1}^{m} H_n \cdot \Theta\left(W_{P,n}\right) \qquad (2)$$

H_n	outage rate of the individual asset in 1/a.
$W_{C,n}$	non delivered energy caused by the individual asset *n* in MWh.
$W_{P,n}$	non feed in energy of power plants caused by the individual asset *n* in MWh.
n	identification number of the individual asset.

W_C is the overall summarized non-delivered energy which is caused by outages and N_C is the number of assets that are responsible for not delivered energy in the 110 kV network groups. In the same case W_P is the accumulated non feed in energy of the power plants in the network and N_P is the number of asset which causes non feed in energy.

In Figure 3 on the left side a comparison of the outage rates H_C and H_P within the ten load scenarios is shown. It is recognizable that there are considerable differences between the two values within the same scenario.



Comparison of summarized outage rates

10 load scenarios		peak load scenario	
$H_{C,ACC}$ in 1/a	$H_{P,ACC}$ in 1/a	H_C in 1/a	H_P in 1/a
0.7006	0.8887	0.4804	0.5739

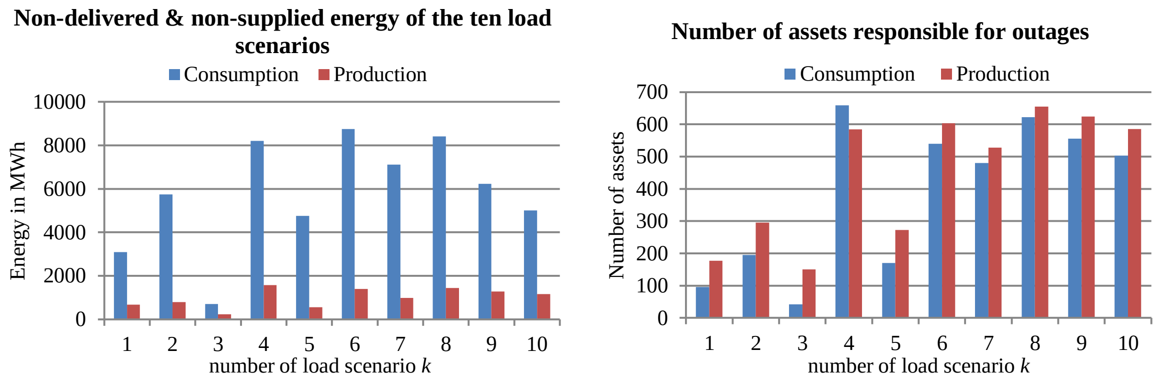
Figure 3: Summarized outage rates of peak load & 10 load scenario analysis.

Marco.Fleckenstein@eev.tu-darmstadt.de

This means that an asset failure does not necessarily have the same impact on production and on consumption. Through the connections to other TSOs shortages or overproductions of energy can be obtained or disposed. The accumulated outage rates in scenarios with increased load, scenario 1 – 4, have not as expected the highest values. The high outage rates in the low load scenarios, number 8 – 10, are caused by the switched off power plant units with high-power gradients. The flexibility of these units is missing. The comparison of the analysis of peak load evaluation with the ten load scenarios, In Figure 2 right side, shows that the expected overall outage rate of the peak load scenario with average outage rates is clearly too low. The accumulated outage rate of the ten load scenario with age-dependent outage rates is significant higher. Thus, here the values refer to the same observation period. The $H_{\mathrm{C,ACC}}$ and $H_{\mathrm{P,ACC}}$ are determined from the summation of all H_{C} and H_{P} of the ten load scenarios. Comparing the summed outage rates of peak load with the average- and age-dependent asset outage rates are the summarized age-dependent values are 15 percent higher for production and 13 percent higher for the consumption of the 110 kV network groups.

Considering the amount of energies W_{C} and W_{P}, Figure 4 left side, the peak load is not the worst case scenario. The scenarios with the medium load, scenario 4-8, generate the highest amounts of non-delivered energy to the 110 kV network groups. The difference of W_{C} and W_{P} in peak load with average-and age-dependent outage rates behaves identically to the accumulated outage rates. The summarized age-dependent values are around 15 percent higher.

The W_{P} has always significantly lower values than W_{C}. This is explained by the fact that the power plants in the investigated transmission system are mostly on the borders to the neighboring TSOs and thus in many cases do not have to be dispatched.



Non-delivered & non-supplied energy of the ten load scenarios

Number of assets responsible for outages

Figure 4: Energy and number of assets comparison of the ten load scenarios.

The latest key figures which are to be compared are the number of assets that cause non-delivery of energy to the 110 kV network groups, N_{C}, or non-feed in energy from power plants, N_{P}. In Figure 4 on the right side, these two key figures are shown for all load scenarios. It can be seen that especially in the low and medium load scenarios, Scenario 6 - 10, a lot of assets cause outages. However, these have in many times low values of W_{C} and W_{P}. In most cases, these are prevented by power plants in the underlying voltage levels or are bypassed by short overload of assets. There are no differences between the average- and age-dependent values.

Nevertheless, it should be noted, that the transmission system is in the low load scenario is more vulnerable than in the heavy load situations. The results of the reliability calculation are different in each load situation. The peak load scenario is not the worst case in any key figure of the reliability and availability calculations. The analysis of the energy not supplied of the individual assets shows that the peak load evaluation differs greatly. With the function K*(n)*, equation 3, the gap between these results is shown.

$$K(n) = \frac{W_{C,TL,n} - W_{C,Peak,n}}{W_{C,TL,n}} \cdot 100\,\% \tag{3}$$

$W_{C,Peak,n}$ non delivered energy caused by the individual asset *n* during the Peak load with averaged outage rate in MWh.

$W_{C,TL,n}$ averaged non delivered energy caused by the individual asset *n* with age-dependent outage rate within the ten load scenarios in MWh.

In Figure 5 the sorted by size plot of the function K*(n)* for all assets is presented. The values above the zero percent line are assets that are underestimated by the peak load method. Values below are overestimated. The graph shows clearly that majority of assets, more than 60 percent, are underrated with the average values and the peak load scenario. Only a few assets can be properly assessed with the peak-load approach. Thus it is shown that for accurate analysis and evaluation of the assets in the transmission network several load flows and the age of the equipment must be taken into account.

Marco.Fleckenstein@eev.tu-darmstadt.de

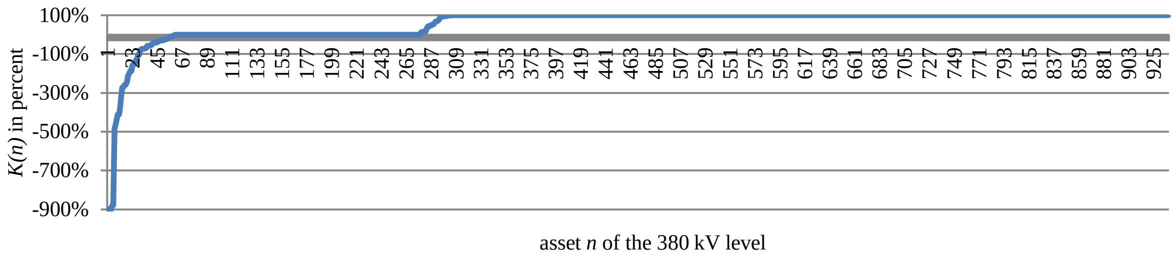


Figure 5: Comparison function *K(n)* of the assets in the 380 kV level sorted by size.

4. Conclusion

Solely from the reliability and availability calculations of the peak-load scenario no evaluations of the significance of the individual asset can be determined. In the medium and low voltage level, this approach is possible. In the transmission network, however, this cannot be done. Too many assets are not depicted correctly in a peak load approach. In this case the dispatching, scheduling and local positions of power plants are very important and must be regarded in the asset assessment in the transmission network. For the development of RBM strategies more reliability and availability calculations based on a variety of network load conditions are necessary for the asset assessment. The influence of age-dependent failure rates should not be underestimated. The fault in a whole is over 15 percent, but which do not reflect the differences in detail.

In further work, the transmission network model will be developed to enable the creation of RBM strategies for the extra high voltage transmission system. The results in this paper are the basis for the creation of Value at Risk controlled RBM-strategies for circuit breakers and center break disconnectors in transmission systems [6][13].

Acknowledgement

The authors of this paper thank the DFG (German Research Association). The DFG supports the author Marco Fleckenstein financially during his PhD thesis: Risk-based maintenance, based on the Value-at-Risk method in the high voltage transmission network.

BIBLIOGRAPHY

[1] Hänsch K., Barrett. S.: Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity, Official Journal L 027, 30/01/1997 P. 0020-0029.

[2] BCP Switzerland Busarello + Cott + Partner AG, „NEPLAN User's Guide V5," Zurich, 2012.

[3] Shakib Danesh, A., "Long distance Transmission of wind energy," in Report FAZ A 201 04, Darmstadt, 2007.

[4] Fleckenstein M., Rhein A., Braun S., Balzer G.: Risk-based maintenance of overhead lines in 380 kV transmission system; XIIICHLIE, Valencia, 3-5 July 2013, Paper 106

[5] Schwan, M., "Using the VDN Statistic on Incidents to Derive Component Reliability Data for Probabilistic Reliability Analyses," Berlin, 2005.

[6] Fleckenstein M., Neumann C., Balzer. G.: Value at risk monitored maintenance for extra high voltage assets, CIGRE Symposium Auckland, 14-20 September 2013, Paper 48.

[7] Umweltbundesamt, "Database: Power Plants in Germany," Dessau-Roßlau, 2011.

[8] Alt, H.: "Permissible load gradients of large power plants" (Original title: Zulässige Lastgradienten von Großkraftwerken), Elektrische Energieversorgung und Verteilung, Hochschule Aachen, 2011.

[9] Swider, D. J., „Trading on standby energy- and spotmarkets" (Original title: Handel an Regelenergie- und Spotmärkten.), Universität Stuttgart. Stuttgart, 2006.

[10] Al, E. "Compatibility of renewable energy and nuclear energy generation portfolio" (Original title: Verträglichkeit von erneuerbaren Energien und Kernenergie im Erzeugungsportfolio.), Universität Stuttgart. Stuttgart, 2009.

[11] Kirsch, R., "Impact of renewable energies on the network stability and the operation of conventional power plants" (Original title: Einfluss der Regenerativen Energien auf die Netzstabilität und den Betrieb von konventionellen Kraftwerken.) Zittau, 2011.

[12] BMU: Act on Granting Priority to Renewable Energy (Renewable Energy Sources Act - EEG) 2012.

[13] Fleckenstein M., Neumann C., Balzer. G.: Importance oriented maintenance strategies based on the value at risk method. CIGRE Colloquium Brisbane, 9-11 September 2013, Paper 170.

Marco.Fleckenstein@eev.tu-darmstadt.de