Journal of Polish Safety and Reliability Association
Summer Safety and Reliability Seminars, Volume 6, Number 3, 2015

Berg Heinz-Peter

Fritze Nicole
Bundesamt für Strahlenschutz, Salzgitter, Germany

Reliability and vulnerability of transformers for electricity transmission and distribution

Keywords

critical infrastructure, transformer, reliability, ageing, blackouts

Abstract

In the last years the failure frequency of transformers increased, e.g. due to ageing or external hazards. In particular fires and explosions of main oil-filled transformers are considered as critical. Therefore, international experiences of transformer failures at nuclear and non-nuclear power plants and at substations have been investigated in more detail. Consequences of transformer failures with respect to a reliable electricity transmission and distribution as well as measures to enhance the reliability of critical infrastructure and to avoid blackouts are addressed.

1. Introduction

Experience worldwide has shown that consequences of events such as voltage surges, lightning strikes, structural damage, and rapid unexpected deterioration of insulation, sabotage, and even maintenance errors can be severe and have the potential to lead to local blackouts or even a blackout that impacts a larger area. A regional blackout lasting more than several days could already be considered as a worst case scenario. Most back-up and security systems will fail after a longer period without electric power, leading to an almost complete failure of most critical infrastructures.

One of the key components in the grid is the power transformer which allows for power transmission and distribution at the required voltage level. Therefore, the reliability of transformers is a prime concern to grid operators. In recent years the failure frequency of transformers increased. In particular fires and explosions of main oil-filled transformers are considered as critical.

A fire of an oil-filled transformer that contains several thousand liters of combustible insulating oil and a consequential explosion can destroy not only the transformer itself, but also nearby transformers. Many experts anticipate that the number of failures per year will increase significantly in the near future. Because about 115 000 large transformers are in operation in the US and about 400 000 worldwide, the number of impacted transformers is high, even when only in some cases fire and explosion lead to a total damage.

Power transformers with an upper voltage of more than 100 kV are necessary for the undisturbed operations of a developed society. In electricity generation plants, power transformers transform the voltage of the generator to a higher level for the transmission of electricity in the main grid. The voltage of the main grid must again be transformed to a lower voltage, so that the electrical energy can be utilized in numerous purposes.

Electric power is normally generated in a power station at 11 to 25 kV. In order to enable the transmission lines to carry the electricity efficiently over long distances, the low generator voltage has to be increased to a higher transmission voltage by a step-up transformer, i.e. 75 kV, 400 kV, 220 kV or 110 kV as necessary. Supported by tall metal towers, the lines transporting these voltages can run into hundreds of kilometers. The grid voltage has then to be reduced to a sub-transmission voltage, typically 26 kV, 33 kV or 69 kV, in power substations.

Sub-transmission lines supply power from terminal stations to large industrial customers and other lower voltage terminal stations, where the voltage is stepped down to 11 kV for load points through a distribution network lines. Finally, the transmission voltage is reduced to the level adapted for household use, i.e. 415 V (3-phase) or 240 V (1-phase) at distribution substations adjacent to the residential, commercial and small to medium industrial customers in the US, in Europe the transmission voltage is reduced to 400 V or 230 V.

Figure 1 shows a typical electrical network system, in which power is transformed to the voltages most suitable for the different parts of the system [25].

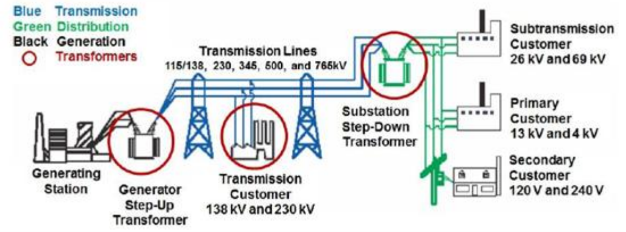


Figure 1. Typical electrical power network

At every point where there is a change in voltage, a transformer is needed that steps the voltage either up or down. There are essentially five levels of voltages in the US [26] used for transmitting and distributing alternating current (AC) power as listed in *Table 1*.

Table 1. Distribution and transmission voltage classes

Class	Voltage Ratings (kV)
Distribution voltage	2.5 to 35 kV
Medium voltage (MV)	34.5 to 115 kV
High voltage (HV)	115 to 230 kV
Extra-High voltage (EHV)	345 to 765 kV
Ultra-High Voltage (UHV)	1100 kV

The UHV, EHV, HV, and MV equipment is mainly located at power plants or at substations in the electric grid representing high voltage electric systems facilities used to switch generators, equipment and circuits or lines of the system on and out, while distribution-level transformers are located in the distribution network on poles, in buildings, in service vaults, or on outdoor pads.

As electricity transport is most efficient at high voltage, transformers at generating stations step up low-voltage power from generation plants and use thousands of kilometres (e. g. in the U.S. about 340,000 km) of high-voltage transmission lines to move power over substantial distances to distribution systems, where transformers step down the voltage for customer use.

Distribution substations lower the voltage of electricity and send it through a network of lines that deliver it to the consumer. Also in the European Union, all countries use the AC electrical supply system.

Since power transformers are so important and extremely complex, transformers are usually the most expensive asset on an electric grid system, and some utilities have thousands of units installed. For the different activities of changing voltage dry type and liquid (mainly oil) insulated transformers are commonly used.

To make matters more complex, the lead time to purchase and receive a new transformer can be about two years in some cases. As these transformers age, and as they see more and more faults on the system, it becomes increasingly important to know the condition of each transformer on the grid, and to have a plan in place to maintain and ultimately replace these transformers [11].

2. International experiences of transformer failures

When a transformer fails, the results are often catastrophic. If the failure was not caused by an existing fire, the potential for a new fire resulting from the failure is extremely high. A power substation by its nature contains all of the right ingredients to generate the perfect fire storm. A typical substation transformer bank is comprised of three or more transformer tanks, each containing up to 170,000 litre of extremely flammable mineral oil. The ignition of the transformer oil can arise from several sources including solid particles of insulation and conductor that are produced by incipient arcing fault, internal component failure, or short circuit electrical arcing inside the tank, any of which can generate resulting heat and pressure sufficient to cause the tank to rupture. Therefore, it is worthwhile to investigate existing international databases to get more detailed information.

The most important international fire database for nuclear power plants is the OECD FIRE Database [20]. Today records for 438 fire events from nuclear power plants in 12 of the OCED/NEA member countries are included in this database providing a reasonable source of qualitative and quantitative information, e. g., on location of the fire, affected component(s), and process and event duration. This database has been analysed with respect to fires of high, medium and low voltage transformers.

The fires in high voltage transformers are distinguished in catastrophic and non-catastrophic failures. A catastrophic failure of a large transformer is defined as an energetic failure of the transformer that includes a rupture of the transformer tank, oil spill and burning oil spattered at a distance from the transformer whereas the non-catastrophic failure includes the high voltage power transformers typically installed in the yard [7].

Medium or low voltage transformers include all transformers with a voltage level < 50 kV. Examples are transformers attached to AC load centres, low voltage regulators, and essential service lighting transformers.

Dry and oil-filled medium or low voltage transformers are typically cabinet external transformers with lower fire load.

Among the reported 438 fire events, transformers are the most frequent fire source with in total 54 events representing an amount of 12.3 % of all fires in the OECD FIRE database. Most of them are fires of high voltage transformers (31 events) and the majority of these transformer fires have to be classified as catastrophic as shown in *Figure 2*.

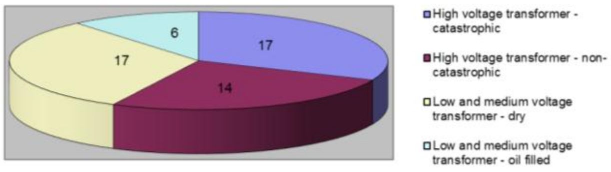


Figure 2. Transformer fires

25 of these 31 events occurred during full power, after the fire in 13 cases the plants have to be shut down. No plant was at the time of the fire in shutdown, and only in two cases the operation mode of the nuclear power plant did not change after the fire.

The majority of transformer fires as listed in *Table 2* occurred at high voltage oil-filled transformer in the transformer switchyard and outside the technical buildings (such as electrical building, auxiliary building, reactor building and turbine building).

Within the document on fire PRA methodology [12] some generic fire frequencies are provided based on the operational experience of US nuclear power plants:

- Catastrophic fires at transformer yard: $6 \cdot 10^{3}$ per reactor year,
- Non Catastrophic fires at transformer yard: $1.2 \cdot 10^{-2}$ per reactor year,
- Other fires at transformer yards: $2.2 \cdot 10^{-3}$ per reactor year.

These values are based on 1674 reactor years and about 35 fire events in total and are comparable with the operating experience from the OECD FIRE database.

Table 2. Transformer fires – area where the transformer fire started

Area	**Transformer type**		
	HV oil-filled	**MV or LV oil-filled**	**MV or LV dry**
Switchyard	**6**	**2**	**2**
Reactor Building	**-**	**-**	**4**
Electrical Building	**2**	**1**	**4**
Turbine Building	**1**	**-**	**1**
Auxiliary Building	**-**	**-**	**4**
Transformer yard/outside	**15**	**2**	**-**
Other building / area	**7**	**1**	**1**
unknown	**-**	**-**	**1**
Total	**31**	**6**	**17**

According to [15] the contribution of the different main components to major failures are winding and on load tap changes (OLTC) with about 25 % each, whereas high voltage (HV) bushings are the cause in about 20 % to 40 % of failures depending on the underlying statistical basis. However, HV bushings provide the highest contribution to all transformer fires with about 70 %. These results are supported by further experience provided in *Table 3* [13]. The underlying database contains 175 transformer failures that resulted in 110 high energy arcs causing in total 44 tank ruptures and 18 fires. In 13 of the 18 fire events, the component HV bushings contribute to the transformer fires.

Table 3. Failure statistics for 735 kV transformers over 25 years

Component	**Faults**	**Ruptures**	**Fires**
HV bushing	41	19	13
Windings	57	21	3
Core	3	2	1
OLTC	2	1	0
Others	7	1	1

3. Reliability and vulnerability of electricity transmission and distribution

Additionally to direct consequences of transformer explosions and fires to nuclear installations, a further aspect is the reliability and availability of transformers. Large power transformers could be a major concern for the electric power sector, because failure of a single unit can cause temporary service interruption and lead to collateral damages, and experience has shown that it could be difficult to quickly replace transformers. Transformer failures could be caused, among others, by external hazards such as earthquakes or external flooding (tsunami). Moreover, while the life expectancy of a power transformer varies depending on how it is used, ageing of power transformers has to be subject to an increased investigation of potential failure risks in the future.

The replacement of worn out assets is a vital, though costly, activity for electricity distribution network operators. It is essential that limited resources of capital, time, equipment and personnel are allocated to those replacement projects which will have the greatest impact on improving security of supply to customers. The most difficult task is to predict the future reliability of the transformer fleet, and to replace each one in a timely fashion. Meeting the growing demand of the grid while at the same time maintaining system reliability with this ageing fleet will require significant changes in the way energy utilities operate and care for their transformers.

The first step in finding a proper model for the distribution of transformer failures is to find a hazard function that is consistent with the known failure rate of transformers. The lifetime of a transformer is usually presented in the form of a “bathtub curve”. However, actual data reported show that this model fails to represent reality correctly and that there is no significant frequency of claims in the first phase of a transformer’s service life.

A more advanced methodology is described in [7] and illustrated by a case study based on a sample from a population of over 400 extra high-voltage power transformers discussing options to schedule the replacement of 44 transformers which were all commissioned in the year 1965 and, therefore, reach estimated design lifetime of 50 years in 2015 at the latest. Four different options have been analysed:

- Option 1 is to use age alone, i.e. to replace all transformers in 2020.
- Option 2 incorporates location and utilization, i.e. actual age of onset of deterioration probably depends on location (coastal, high altitude or polluted) and on how often transformer has been operating near to its maximum rating. On this basis, the first transformer should be replaced in 2012, and the last in 2030.
- Option 3 uses the so-called health index (HI) to include condition data. This index is commonly used within the electricity distribution industry, in particular in United Kingdom. The HI starts at typically 0.5 for transformer at age 0. Exponential rate of increase of the HI depends on location and utilisation, from 0 up to 10. The HI is linked to expected fault rate. The expected value of the HI is then adjusted based on inspection and analysis.
- Option 4 includes as a further input measures of consequences, e.g., probability of losing supply, number of customers affected, and time to restore supply.

In practice, the use of this methodology described in [7] is modified by other considerations. Safety or environmental concerns, such as a transformer adjacent to a residential area which has become unacceptably noisy, may accelerate a particular replacement. Load growth may require an increase of capacity which leads to the earlier replacement of a bottleneck asset. Assets of the same age, but made by different manufacturers, may differ as regards the ease of obtaining spare parts, and therefore lead to a revised replacement prioritization. And any repeated fault history is likely to move the asset concerned towards the head of the queue. However, despite of all these potential modifications, the methodology in [7] provides a useful and scientifically justified basis for the asset replacement programme.

Another approach focused on thermal degradation of transformer paper insulation and calculating for this specific degradation process the remaining lifetime of power transformers on individual and population level is discussed in [27]. The limited availability of spare extra-high-voltage transformers in crisis situations presents potential supply chain vulnerability [17].

Thus, as a key component of power grids, transformers deserve special attention. As discussed in [26], large power transformers are significant investment pieces that are critical to the reliable operation of the electric grid. Therefore, the assessment of the health of and risks to large power transformers is an essential part of proper maintenance of the equipment. *Figure 3* is an analysis of the main causes of power transformer failures between 1991 and 2010. This figure is based on the examination of historical insurance claims for various utility type transformers during the 20-year period, which included several hundred transformer failures [4], [26].

The leading cause of transformer failures was “line disturbance”. This category includes switching surges, voltage spikes, line faults/flashovers and other utility abnormalities. It does not include lightning. *Figure 3* illustrates the percentage of failures for each cause, i.e. the relative number of failures.

The risk of a transformer failure comprises not only the frequency of failures but also the severity of a failure. The fact that a transformer can fail due to any combination of electrical, mechanical or thermal factors renders the prevention of losses extremely challenging. Yet even rigorous maintenance programmes cannot prevent the often very costly failure of transformers. The complex technology involved in transformers also makes it very difficult to define a typical failure scenario. Nevertheless: in many cases, it is the insulation of the transformer that fails. The result is a failure in the electrical systems caused by weather conditions, quality of manufacture or maintenance and operating factors.

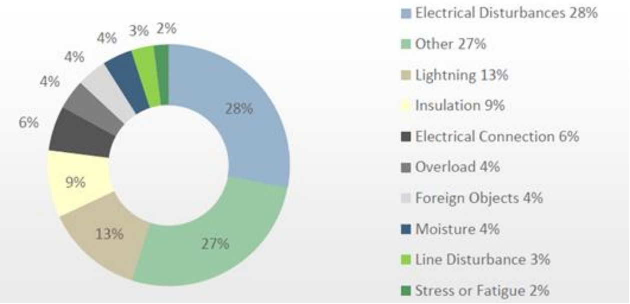


Figure 3. Causes of transformer failure according to [4]

As explained in [22] seven different databases show a very diverging picture of root causes. Three examples are shown in *Figure 4*, representing data from two vendors and the International Council on Large Electrical Systems (CIGRE).

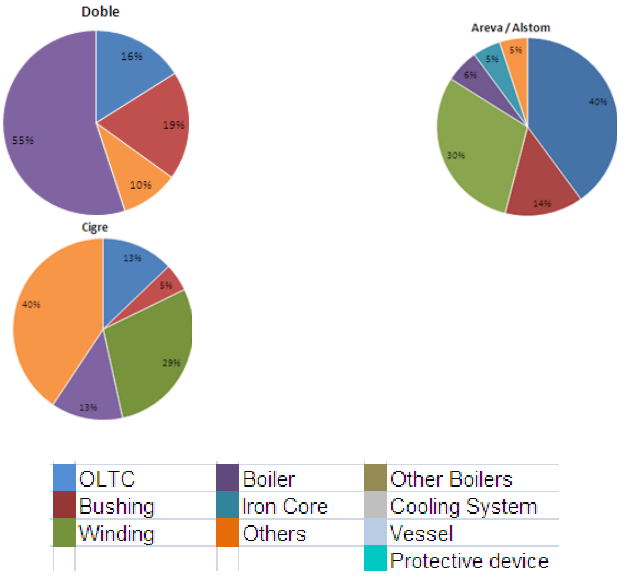
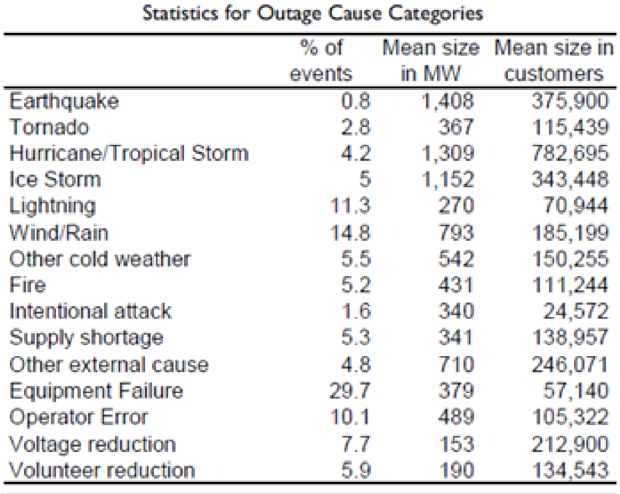


Figure 4. Probability of occurrence of transformer component failures (OLTC=on load tap changers)

Since several years a working group of CIGRE is elaborating a transformer failure survey; however, this document is still under development. On this background additional investigations and research activities are needed in order to develop a consistent and useful database for improving safety and reliability of transformers.
Utilities in the U.S. reached a peak in new substation and transformer installations around 1973 to 1974. During this period, approximately 185,000 MVA (megavolt amperes) of new power transformer capacity was added. These transformers range in size from 5 MVA to 1,000 MVA. Today, those transformers are about 37 years old.
The fact that spending on new or replacement transformers is at its lowest level in decades means that the average age of the USA’s entire transformer population continues to rise. Similarly, in the United Kingdom, energy utility National Grid started recording the installation and movement of its 400 kV and 275 kV power transformers in 1952. In the peak year of 1966, a total transformer capacity of 23,000 MVA was installed in the United Kingdom. Installation numbers dropped significantly after 1966, until utility privatisation in 1989. Afterwards, increased market activity again required a higher level of investment. Today, the majority of the population of transformers in the United Kingdom is over 36 years old.
The highest number of predicted failures is for transformers manufactured in 1974. Adding the predicted failures for transformers dated 1964 to 1992 illustrates the magnitude of the problem. A significant number of failures is predicted for the year 2020.
In particular much of the infrastructure which serves the United Kingdom and U.S. power grid is ageing. In the U.S., the average age of power plants is now over 30 years, with most of these facilities having a life expectancy of 40 years.
Electric transmission and distribution system components are similarly ageing, with power]transformers averaging over 40 years of age and 70% of transmission lines being 25 years old or older. As components of the system are retired, they are replaced with newer components often linked to communications or automated systems.
The North American Electric Reliability Corporation (NERC) requires electric utilities to report events causing disturbances that interrupt service (i.e., power outages) of more than 300 MW or affect 50,000 customers or more. An analysis of NERC data describing 933 events causing outages from the years 1984 to 2006 [8] is presented in *Table III*. Almost 44% of the events in the period were weather-related (i.e., caused by tornado, hurricane, tropical storm, ice storm, lightning, wind/rain, or other cold weather).
Experience has shown that cold weather conditions have led to a contraction of the oil resulting in reaction of the Buchholz relay to shut down the transformer. The Buchholz relay is used as a protective device sensitive to the effects of dielectric failure inside the equipment.

Table 4. Failure statistics for 735 kV transformers over 25 years



Statistics for Outage Cause Categories

	% of events	Mean size in MW	Mean size in customers
Earthquake	0.8	1,408	375,900
Tornado	2.8	367	115,439
Hurricane/Tropical Storm	4.2	1,309	782,695
Ice Storm	5	1,152	343,448
Lightning	11.3	270	70,944
Wind/Rain	14.8	793	185,199
Other cold weather	5.5	542	150,255
Fire	5.2	431	111,244
Intentional attack	1.6	340	24,572
Supply shortage	5.3	341	138,957
Other external cause	4.8	710	246,071
Equipment Failure	29.7	379	57,140
Operator Error	10.1	489	105,322
Voltage reduction	7.7	153	212,900
Volunteer reduction	5.9	190	134,543

The traditional view of the transformer as an uncritical piece of equipment which can be left to go on working without much attention has in the meantime given way to a new view of the transformer as a piece of equipment deserving and requiring the utmost attention. Marginal conditions such as age pattern, delivery situation, and political conditions have made substantial reactions an absolute necessity. Thus, it will be necessary to determine the salvageable residual substance of the members of a population, and to coordinate conservation and necessary replacement through integrated planning and scheduling. Obviously, this planning and scheduling will have to be long-term and allow the implementation and use of all options available.

4. Countermeasures to avoid blackouts

While the majority of power failures from national grids last only a few hours, some blackouts can last days or even weeks, completely shutting down production at companies and critical infrastructures. Therefore, in-depth investigations are performed to collect real data of blackouts and derive appropriate countermeasures.

More and more grids are interconnected, a blackout in one region can trigger a domino effect that could result in supra-regional blackouts. However, statistics show that the situation regarding blackouts in different parts of the world is not comparable. Latin America has one of the lowest numbers of power outages, but they last the longest on average. South Asia, on the other hand, has the highest number of power outages per year, although they usually last only a few hours, the effects are sharply felt. In many cases failures of high-voltage transformers or substations caused these blackouts. In Bangladesh 38,870 transformers out of 715,000 exploded between July 2013 and June 2014 due to overloading or poor quality of transformer components.

The limited availability of extra-high-voltage transformers in crisis situations presents a potential supply chain vulnerability. Although utilities are quite adept at managing their equipment inventories and supply chains, extra-high-voltage transformers in particular may present a weak link in the sector's resilience. These transformers are highly specialized equipment, have 18- to 24-month manufacturing lead times, and are difficult to transport. Industry programs to share spares help to mitigate risks, but the application of this arrangement has been limited in practice [17].

In order to enhance transformer reliability by getting early warning information on the transformer condition, a set of modern diagnostic methods, traditionally categorized as online or offline monitoring, is available and applied for oil-filled power transformers to detect abnormalities in the transformer or one of its components [5, 11]. Detection techniques are furthermore comprised of parametric measurements (investigating, e.g., the current, voltage, internal pressure of the tank, oil level, oil temperature, and gas in oil analysis) and visual inspections (e.g. temperature indicators, level gauges and, in particular, oil leaks which may indicate a potential for oil contamination or loss of insulation).

Defects in transformers can be caused by mechanical, thermal and dielectric stresses either individually or in conjunction. It must be taken into account that the majority of the diagnostic methods are sensitive to all three fundamental stresses acting on the transformer. Therefore, the general interpretations including the localization of faults can be problematic. The experience and interpretation capabilities of transformer experts are crucial for a successful diagnosis.

Thus, knowing the set of potential causes of blackouts managing the risks is an essential part of operating the electric grid. Maintaining the reliability of the electric system should be the overriding objective and is the core of its risk management strategy. In this context, risk is seen as the likelihood that an operating event will reduce the reliability of the electric grid to the point that the consequences are unacceptable. Because it is not possible or practical to prevent all disruptive events, the electric system has to be planned and operated in a manner that the effects are manageable and the consequences are acceptable when events occur.

Cyber vulnerability is addressed in [16]. A targeted attack on extra-high-voltage transformers has been identified as a potential system vulnerability.

In the long run, the security of the grid will also depend on how new technology will be integrated into aging infrastructure. Some of these technologies allow for the move to more resilient “microgrids” with distributed generation. However, while more resilient, such smart grid and microgrid systems present significant challenges to grid security [10].

On March 7, 2014, the Federal Energy Regulatory Commission directed the North American Electric Reliability Corporation to develop mandatory physical security standards within 90 days in the wake of attacks on transmission facilities in the United States.

Owners and operators are to first identify critical facilities, and then develop and implement plans to protect against physical attacks that may compromise the operability or recovery of such facilities.

In addition, the improvement of the physical security of high-voltage transformer substations is seen as a necessary task [21].

The nuclear sector has several interdependencies [14]. Large power plants generally have no electricity power storage capability; therefore, the electricity generated by the plants must immediately be channelled through the transmission lines of the electricity sector.

If all transmission lines to a nuclear power plant are down, the plant must go to cold shutdown for safety purposes.

The technical issues associated with the interface between NPPs and the electric grid include:

- The magnitude and frequency of load rejections and the loss of load to NPPs.
- Grid transients causing degraded voltage and frequency in the power supply of key safety and operational systems of NPPs.
- A complete loss of off-site power to an NPP due to grid disturbances.
- An NPP unit trip causing a grid disturbance resulting in severe degradation of the grid voltage and frequency, or even to the collapse of the power grid.

6. Concluding remarks

Critical assets in the power systems which have remarkable effects from a reliability point of view should be considered with attention to their maintenance and replacement. Transformer is one asset that with a notable role in the power system due to its effect on reliability as well as its extensive investments in the power grid. The significance of transformer necessitates utilities to be concerned about transformer management.

In that context, a bill [24] has recently been introduced in the House of Representatives of the United States which requires the Department of Energy (DOE), acting through the Office of Electricity Delivery and Energy Reliability, to submit to Congress a plan to establish a strategic transformer reserve for the storage, in strategically located facilities, of spare large power transformers in sufficient numbers to temporarily replace critically damaged large power transformers.

The aim of the storage is to “diminish the vulnerability of the United States to multiple risks facing electric grid reliability, including physical attack, cyber-attack, electromagnetic pulse, geomagnetic disturbances, severe weather, and seismic events”[24].

Moreover, the designed life of a transformer is about 40 years, but in practice experience has noted that transformers operate reliable about 20 to 30 years.

Risk assessment for transformers has to study all possible causes for failures and the resulting consequences and is an important part of the proactive risk management process. However, societal crisis management consists of a number of phases, for example: prevent, mitigate, response, recover, and learn.

The preferred risk analysis approach depends on the objective of the analysis, but also on the available information about the system (are there reliable and stable data sets resulting from real accidents?). Safety and reliability methods can to some extent be used to analyze the technical systems that form the infrastructure.

However, reliability modelling approaches for power transformer by using Markov state space models are described in [23]. Moreover, advances in modelling and simulation of complex networks and also game theoretical approaches may be taken into account in the future.

Several events in all types of energy producing power plants and substations have shown that ageing of transformers might be a matter of concern. During transformer life, structural strength and insulating properties of materials used for support and electrical insulation (especially paper) deteriorate. Clamping and isolation can then no longer withstand high energy arcing faults which can result in catastrophic explosions and fires. Thus, a proactive strategy for replacing ageing transformers at due time is needed (see, e. g, [9]).

For that purpose it is necessary to investigate the effect of age related failure of power transformers on the identification of most critical transformer sites for system reliability. The end-of-life failure model of power transformers is modified first to integrate loading conditions effect. The adopted Arrhenius-

Weibull probability distribution, which represents the effect of thermal stress on the transformer's end-of-life failure, was compared with the commonly used Gaussian probability distribution model.

The sensitivity of results to the uncertainty in model parameters is thoroughly assessed, and acceptable level of uncertainty is determined. The results demonstrated the importance of integration of loading conditions into the failure model. The sensitivity analysis revealed that the identification of critical transformer sites is not significantly affected by the uncertainty in the failure model parameters and that approximate ranges of parameters can be used instead of accurate values without significant, if any, loss in accuracy.

Two new probabilistic indicators relating the reliability of transformers to their age and loading levels are developed to rank power transformers based on their criticality for multiple failure events. The first indicator (ICF) identifies which transformers can initiate a sequence of multiple failures when they fail, while the second (VCF) identifies transformers which are the most vulnerable to a consequential failure. The indicators are calculated for individual transformers and transformer sites, and their robustness to load uncertainty is assessed. The case studies were performed on a realistic transmission test system with 154 power transformers. More details are given in [1] – [3].

Moreover, there are concerns about an extreme geomagnetic disturbance event causing a larger number of failures which may ultimately result in the failure of some transformers [18]. Thus, vulnerability assessments, equipment testing, operational procedure enhancements and appropriate measures for grid and facility hardening should be considered to address potential impacts.

Therefore, as explained in [19], the examination of interconnection-wide phenomena is necessary for industry to more effectively address frequency response, inertial response, small-signal stability, extreme contingency impacts, and geomagnetic disturbances. In order to support improved system performance and planning, validated models should accurately represent actual equipment performance in simulations.

All devices and equipment attached to the electric grid must be modeled to accurately capture how that equipment performs under static and system disturbance conditions. Models provided for equipment must be open-source and shareable across the industry to support reliability [19].

References

[1] Awadallah, S.K. E. (2014). *Probabilistic methodology for prioritising replacement of ageing power transformers based on reliability assessment of transmission system*. PhD thesis submitted to The University of Manchester.

[2] Awadallah, S.K. E., Milanovic, J.V. & Jarman, P. (2015). The influence of modeling transformer age related failures on system reliability. *IEEE Transactions on Power Systems* Vol 30, Issue 2, 970-979, March 2015.

[3] Awadallah, S. K. E., Milanović, J. V., Wang, Z. & Jarman, P. N. (2015). Assessment of suitability of different reliability importance measures for prioritising replacement of transmission system components, in: *IEEE Eindhoven PowerTech 2015*; 29 Jun 2015-02 Jul 2015; Eindhoven, The Netherlands.

[4] Bartley, W.H. (2011). Ageing transformers are a risk to the electric power supply. Munich Re *Schadenspiegel*, Issue 2/2011, 14 – 19.

[5] Berg, H.P. & Fritze, N. (2010). Power plant transformer explosion and fire. SSARS 2010 – Summer Safety and Reliability Seminars, *Journal of Polish Safety and Reliability Association*, Volume 1, 35 – 42.

[6] Berg, H.P. & Fritze, N. (2012). Risk and consequences of transformer explosions and fires in nuclear power plants. *Journal of KONBiN* 3(23)2012 ISSN 1895-8281, 05 – 16.

[7] Blake, S., Taylor, P., Black, M. & Miller. D. (2012). Using condition data and fault consequence to inform asset replacement programmes. *Proceedings of the International Colloquium Transformer Research and Asset Management*, Dubrovnik, Croatia.

[8] Campbell, R. J. (2012). *Weather-related power outages and electric system resiliency*. Congressional Research Service, R42696.

[9] Chen, D.P. (2014). *Analyzing transformer replacement policies: a simulation approach to reducing failure risk*. Princeton University, April 2014.

[10] Center for the Study of the Presidency & Congress – CSPC (2014). *Securing the U.S. electrical grid*. Washington, D.C. First Edition, July 2014.

[11] Elkinson, K., McGrail, T. & Topjian, G (2012). Transformers: the backbone of our society. Proceedings of the International *Colloquium Transformer Research and Asset Management*, Dubrovnik, Croatia.

[12] EPRI and USNRC. (2005). *EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities; Volume 2: Detailed Methodology*. EPRI TR-

101/1089 and NUREG/CR-6850, Electric Power Research Institute and U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research.

[13] Foata, M. & Nguyen, V. N. (2010). *Transformer tank rupture and mitigation – Hydro-Quebec perspective*, Presentation.

[14] International Atomic Energy Agency - IAEA (2012). *Electrical grid reliability and interface with nuclear power plants*. IAEA Nuclear Energy Series, No. NG-T-3.8.

[15] Lord, T. & Hodge, G. (2008). Online monitoring of transformers as a strategic tool.

[16] National Academy of Sciences – NAS (2012). *Terrorism and the electric power delivery system*. National Academic Press, Washington, D.C.

[17] National Infrastructure Advisory Council – NIAC (2010). *A framework for establishing critical infrastructure resilience goals*.

[18] North American Electric Reliability Corporation – NERC (2012). *Long-term reliability assessment*, November 2012.

[19] North American Electric Reliability Corporation – NERC (2014). *Long-term reliability assessment*, November 2014.

[20] Organisation for Economic Co-operation and Development - OECD. Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI), (2012) *OECD FIRE Database, Version: OECD FIRE DB 2013:1*, Paris, France, August 2014.

[21] Parformak, P.W. (2014). *Physical security of the U.S. power grid: high-voltage transformer substations*. Congress Research Service, R43604, June 2014.

[22] Steindl, E. (2012). Risk management and transformer monitoring. Presentation at the *International Colloquium Transformer Research and Asset Management*, Dubrovnik, Croatia.

[23] Tang, S., Hale, C. & Thaker, H. (2014). Reliability modeling of power transformers with maintenance outage. *Systems Science & Control Engineering: An Open Access Journal*, 2:1, 316-324.

[24] U.S. Government Publishing Office – GPO (2015). *H. R. 2244, a bill to establish a strategic transformer reserve*, May 8, 2015.

[25] United States Department of Energy (2012). *Large power transformers and the U.S. electrical grid*, DOE/OE/ISER, June 2012.

[26] United States Department of Energy (2014). *Large power transformers and the U.S. electrical grid*, DOE/OE/ISER, April 2014 Update.

[27] Wouters, P., van Schindel, A. & Wetzer, J. (2010). Remaining lifetime modelling of power transformers on individual and population level. *International Conference on Solid Dielectrics, Potsdam*, Germany, July 4-9, 2010.