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Reliability and vulnerability of critical infrastructure – electricity distribution

Keywords

critical infrastructure, reliability, transformer, ageing, failure statistics, blackouts

Abstract

In recent years the failure frequency of transformers increased. 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 electric power supply and distribution are addressed and proactive measures to enhance the reliability of critical infrastructure and to avoid blackouts are described.

1. Introduction

Experience worldwide has shown that consequences of events such as voltage surges, lightning strikes, structural damage, 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, in terms of both reliability and investment, is the power transformer, which allows for power transmission and distribution at the required voltage level. The reliability of transformers is, thus, 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 litres of combustible insulating oil and a consequential explosion can destroy not only the transformer itself, but also nearby transformers. Investigations have discovered 730 transformer explosions in the USA only within one year.

Many experts anticipate that the number of failures per year will increase significantly in the near future to 2%. In addition, the shorter lifetime of new transformers will sharply increase above this rate in the next years.

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. Therefore, transformers are installed at the side of generation and in transmission and distribution (see *Figure 1*).

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.

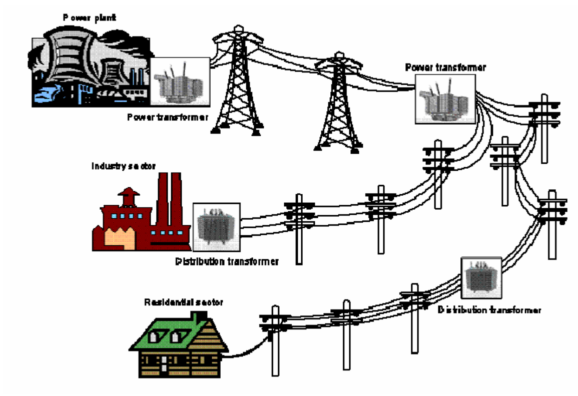

Figure 1. Electricity transmission and distribution system

Supported by tall metal towers, the lines transporting these voltages can run into hundreds of kilometres. The grid voltage has then to be reduced to a sub-transmission voltage, typically 26 kV, 33 kV or 69 kV, in terminal stations (also known as 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 2 shows a typical electrical network system, in which power is transformed to the voltages most suitable for the different parts of the system [16].

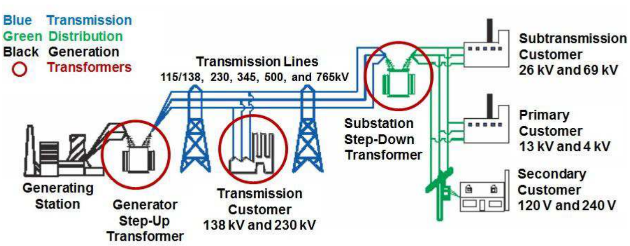

Figure 2. Typical electrical power network

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 (United States Department of Energy 2006) used for transmitting and distributing alternating current (AC) power (*Table 1*): Ultra-High Voltage (UHV, 1100 kV), Extra-High Voltage (EHV, 345 to 765 kV), High Voltage (HV, 115 to 230 kV), medium (or sub-transmission) voltage (MV, 34.5 to 115 kV), and distribution voltage (2.5 to 35 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.

Substations can be large with several transformers and dozens of switches.

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 kilometers (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.

Table 1. Alternative current voltage classes

Transmission Voltages		**Distribution Voltages**	
Class	**kV**	**Class**	**kV**
Medium voltage (MV)	34,5	2.5	2.4
	46	5	4.16
	69	8.66	7.2
	115	15	12.47
High voltage (HV)	115	25	22.9
	138	35	32.5
	161		
	230		
Extra-High voltage (EHV)	345		
	500		
	765		
Ultra-High voltage (UHV)	1100		

Distribution substations lower the voltage of electricity and send it through a network of lines that deliver it to businesses and residences.

Also in the European Union, all countries use the AC electrical supply system.

Since power transformers are so important, and because they are 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 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 [9].

Of course, to know the condition of each transformer on the grid is a daunting task. There are utilities that own and operate thousands of transformers, some of which have been in service for over four decades. Knowing which of these transformers may be the next to fail is easier said than done.

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 [19]. Today records for 415 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), process and event duration. This database has been analyzed with respect to transformer fires for 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 [4].

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 415 fire events, transformers are the most frequent fire source with in total 52 events representing an amount of 12.5 % of all fires in the OECD FIRE database.

Most of them are fires of high voltage (oil-filled) transformers (29 events) and the majority of these transformer fires have to be classified as catastrophic as shown in *Figure 3*.

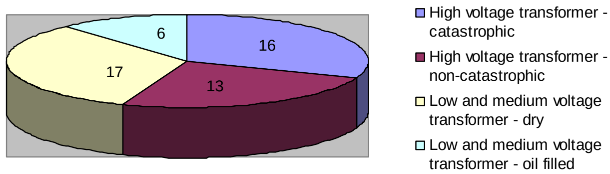

Figure 3. Transformer fires

24 of these 29 events occurred during full power, after the fire in 12 cases the plants have to be shut down. No plant was at the time of the fire in shutdown, and only in three cases the operation mode of the nuclear power plant did not change after the fire.

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	5	2	2
Reactor Building	-	-	4
Electrical Building	2	1	4
Turbine Building	-	-	1
Auxiliary Building	-	-	4
Transformer yard/outside	18	3	-
Other building / area	4	-	1
unknown	-	-	1
Total	29	6	17

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 the electrical building, the auxiliary building, the reactor building and the turbine building).

Within the document on fire PRA methodology [10] some generic fire frequencies are provided based on the operational experience of US nuclear power plants:

- Catastrophic fires at transformer yard (including events with rupture of transformer tank, oil spill and burning oil splattered a distance from the transformer): $6 \cdot 10^{-3}$ per reactor year.
- Non Catastrophic fires at transformer yard (including events without oil spill outside transformer tank): $1.2 \cdot 10^{-2}$ per reactor year.
- Other fires at transformer yards (including events associated with the transformers but not the transformers themselves): $2.2 \cdot 10^{-3}$ per reactor year.

The above given mean values are based on 1674 reactor years and about 35 fire events in total. These transformer yards' fire frequencies are comparable with the operating experience from the OECD FIRE database [3].
More recent industry data show that in case of substation transformer 20 % of failures result in a fire. In Los Angeles, 97 transformer fires occurred in the first three month of 2006, averaging more than one per day.
According to [13] 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* [12].

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

This 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.

The large contribution of bushing failures to the transformer fire risk is also a result presented in the last transformer session of the International Council of Large Electric Systems [11] as shown in *Figure 4*.

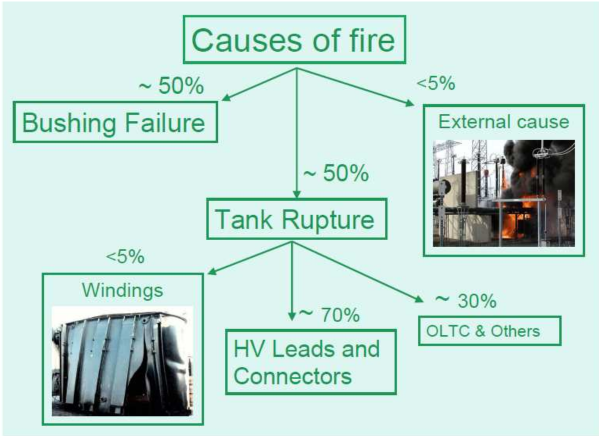

Figure 4. Causes of transformer fires

3. Reliability and vulnerability of critical infrastructure

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”.

Accordingly, an initial short phase with many failures is followed by a longer phase with a very low risk of failure, before a significant increase occurs again in the third phase. 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 [5] 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. Advantages and disadvantages of this option are

- Impracticable because replacing over 10% of asset base in a single year would be beyond the financial, organizational and manpower resources of the network operator.
- Inefficient because the 44 transformers will in practice have deteriorated at different rates over their lifetimes.

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. Advantages and disadvantages of this option are

- Spreads out the replacements over an 18 year period.
- Avoids replacing transformers before they are worn out.
- However, starting the programme (for the worst locations and most used transformers) is now urgent.
- Does not take account of actual transformer condition (determined by inspection, and by analysis of oil, dissolved gases).

Option 3 uses the so-called health index to include condition data. This index is commonly used within the electricity distribution industry, in particular in United Kingdom [18].

The health index starts at typically 0.5 for transformer at age 0. Exponential rate of increase of the health index depends on location and utilisation, from 0 up to 10. The health index HI is linked to expected fault rate. The expected value of the health index is then adjusted based on inspection and analysis.

The relationship between the health index and the expected condition-related fault rate is then shown by the failure probability curve depicted in *Figure 5*.

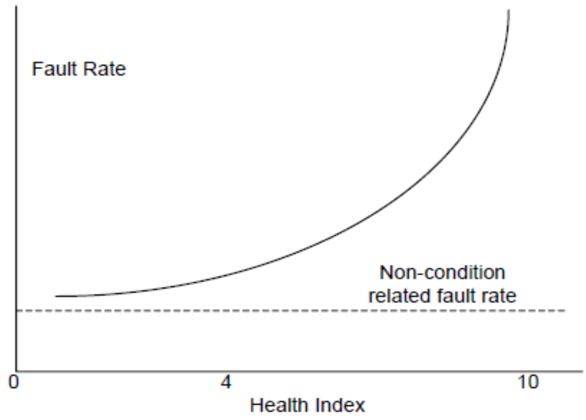

Figure 5. Health index related failure probability curve

Advantages and disadvantages of the option applying the health index are

- Simple rule can be adopted, for example replacement when HI reaches 8.0.
- Transformer replacement can be accelerated by including condition data (e.g. from 2023 to 2016) or deferred (e.g. from 2018 to 2031) or stay the same.
- Less likely to replace a transformer too early (unnecessary cost) or too late (unnecessary risk).
- But this method still does not take into account the relative importance of different transformers.

Option 4 includes as a further input measures of consequences, e.g., the probability of loosing supply, number of customers affected, and time taken to restore supply. Advantages and disadvantages of this option are

- Replacement carried out earlier, at lower levels of risk, for more critical assets (e.g. with many customers).
- Higher risk can be tolerated, and replacement deferred for less critical assets.
- But the replacement schedule becomes more complex when measures of consequence are included.

In practice, the use of this methodology described in [5] 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 [5] 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 [22].
The limited availability of spare extra-high-voltage transformers in crisis situations presents potential supply chain vulnerability [15].
Thus, as a key component of power grids, transformers deserve special attention. An alarming analysis [1] shows that many power transformers used in the electricity supply are old and could cause major losses in the coming years.
The leading cause of transformer failures reported between 1991 and 2010 was “line disturbance” [1]. This category includes switching surges, voltage spikes, line faults/flashovers and other utility abnormalities. It does not include lightning.
Figure 6 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.

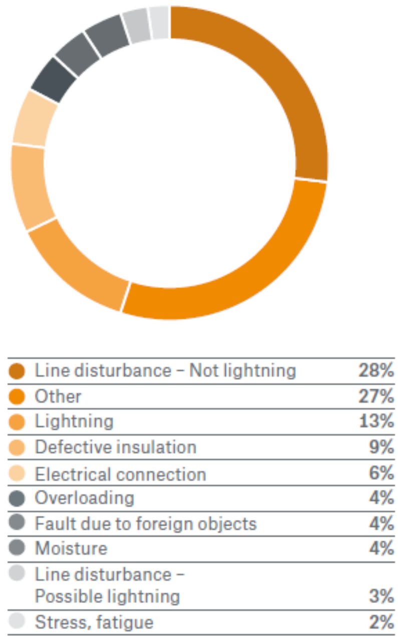

Figure 6. Causes of transformer failure according to [1]

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. After privatisation, 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. We predict a significant number of failures for the year 2020.
Electrical power from a utility can be disturbed or even cut [8] by:

1) Atmospheric phenomena affecting overhead lines or buried cables:

- lightning which can produce a sudden voltage surge in the system,
- frost which can accumulate on overhead lines and cause them to break,

2) Accidents:
   - a branch falling on a line, which may produce a short-circuit or break the line,
   - cutting of a cable, for example during trench digging or other construction work,
   - a fault on the utility power system,
3) Phase unbalance,
4) Switching of protection or control devices in the utility power system, for load shedding or maintenance purposes.

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 [7] is presented in *Table 4*.

According to [7] 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).

Table 4. Large Blackouts in the United States

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

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.

In [7] it is noted that the data include many events smaller than the NERC reporting threshold. It also noted that some of the reported events have “multiple initiating” causes, since some events (such as lightning) can trigger other outages or operator errors.

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.

A very different course of action is therefore of the essence: 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.

Also, as more and more grids are interconnected, a blackout in one region can trigger a domino effect that could result in supra-regional blackouts. Heightened risk from terrorism, cyber attacks and solar flares also highlights how vulnerable the world’s energy grids are to systemic failure.

However, statistics show that the situation regarding blackouts in different parts of the world is not comparable. *Figure 7* illustrates the outages per year and duration for the year 2009.

As one can see from *Figure 7*, 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.

Figure 7. Outages per year and duration for the year 2009

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. Their high cost limits the ability of utilities to maintain many spares, which are often co-located at substations, thereby increasing their vulnerability. Industry programs to share spares help to mitigate risks, but the application of this arrangement has been limited in practice [15].

Typically power blackouts are not caused by a single event but in most cases by a combination of several deficiencies. There is no outage known where a faultless grid collapsed completely due to one single cause [6].

Potential causes of power blackouts are depicted in *Figure 8*.

The following preconditions are the basis for a high power outage risk:

- High grid utilisation or high power demand.
- High power plant utilisation.
- Defects due to material ageing.

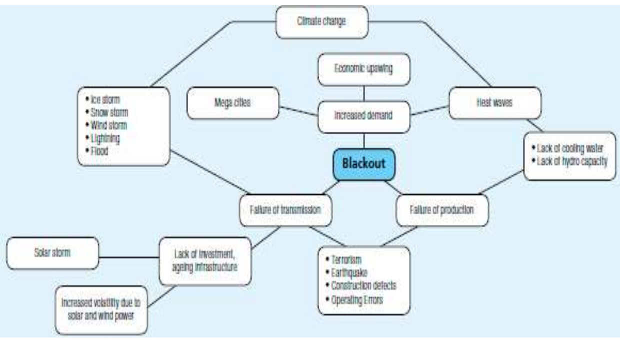

Figure 8. Potential causes of power blackouts according to [6]

If the following events occur in combination with the above mentioned conditions there is a very high likelihood for a power blackout to occur:

- Power plant shutdown for revision or due to supply failures (e.g. cooling water shortage during heat waves).
- Unforeseen simultaneous interruptions of several power plants.
- Human failure during maintenance work or switching operations.
- Simultaneous grid interruption e.g. short circuit caused by tree contact, excavation work, balloons drifting into power lines, cars hitting utility poles, provisional shutdown due to electrical overloading risk.
- Sudden simultaneous high power demand, e.g. simultaneous usage of air conditions during hot summers.
- Power line collapse or electrical equipment breakdown due to natural hazards (e.g. wind, earthquake, snow or ice load, flood, lightning, space weather, extreme temperatures).
- Insufficient communication between transmission/distribution system operators (TSO/DSO) and power suppliers.
- Cyber attacks.

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 [2, 9].

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 recently addressed in [14]. A targeted attack on extra-high-voltage transformers, for example, has been identified as a concern and potential system vulnerability. Besides being very expensive, large, and hard to move, spare transformers have a long lead time in their production. Most are manufactured overseas, and must be custom designed to fit into the location-specific grid configuration.

A recent report [21] on large power transformers provides the following observations:

- Demand for large power transformers is on the rise globally and domestically.
- Two key raw materials – copper and electrical steel – are vital to large power transformer manufacturing.
- Large power transformers require a long lead time and transporting them can be challenging.
- The U.S. has limited production capability to manufacture large power transformers.
- However, domestic production of large power transformers is expected to improve in the near future.
- A current effort by the North American Electric Reliability Corporation may enhance understanding of large power transformer spares.
- A new developed recovery transformer concept may provide some relief.

These observations have to be picked up by the electricity sector in planning the following countermeasures to avoid blackouts:

- Reduce co-location of spare transformers with the units they intend to replace to avoid damage to spare units when operating units fail.
- Increase the number of spare transformers in the Edison Electric Institute (EEI) Spare Transformer Equipment Program (STEP), a coordinated industry program to build up the inventory and to streamline the delivery process in the case of a disaster.
- Further research and development of a recovery transformer (lighter, smaller and quicker to install) to be used temporarily until a new transformer is available.
- Research the possibility of building standardized transformers to reduce the number of uniquely designed units.

Electric grid operators have decades of experience in weather emergencies and natural disasters and have built on that experience to integrate effective response and recovery capabilities into primary grid operations. Experience makes threats from ageing infrastructure, hurricanes, floods, icing, and other physical stresses better quantifiable and more manageable.

The nuclear sector has several interdependencies. The most important of these is the electricity sector. 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, then the plant must go to cold shutdown for safety purposes. On the other hand, the electricity sector in many regions, e.g. of the USA, France or Japan, strongly depends on the nuclear sector for a reliable source of electricity to stabilize the grid and enable the efficient distribution of the load.

5. 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. Transformer management is comprised not only of identifying the appropriate type and frequency to maintain the transformer, but also the appropriate time for replacement. As a result, maintenance and replacement approaches should not be decoupled from each other.

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.

When identifying actions and measures to protect the infrastructure systems, the whole disturbance process needs to be considered. Minimizing the duration of a power outage might in some situations be a more effective allocation of resources than using the resources to trying to prevent the event from occurring.

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?). Methods from the systems safety and reliability discipline can to some extent be used to analyze the technical systems that form the infrastructure.

However, 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 not longer withstand high energy arcing faults which can result in catastrophic explosions and fires. Especially explosion resulting in a fire is of great concern and importance.

Thus, transformer age might be an important factor to consider when identifying candidates for replacement or rehabilitation.

One major problem for all these considerations is the lack of a reliable and transparent database describing which component is the faultiest one.

As explained in [20] seven different databases show a very diverging picture of root causes. Four examples are shown in *Figure 9*, representing data from three vendors and the International Council on Large Electrical Systems (CIGRE). 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.

In general the industry is well-equipped to face a small number of transformer failures; however, there are concerns about an extreme geomagnetic disturbance event causing a larger than expected number of failures which can result in transformer damage and may ultimately result in the failure of some transformers [17].

A potential trigger for large-scale blackouts may be space weather events.

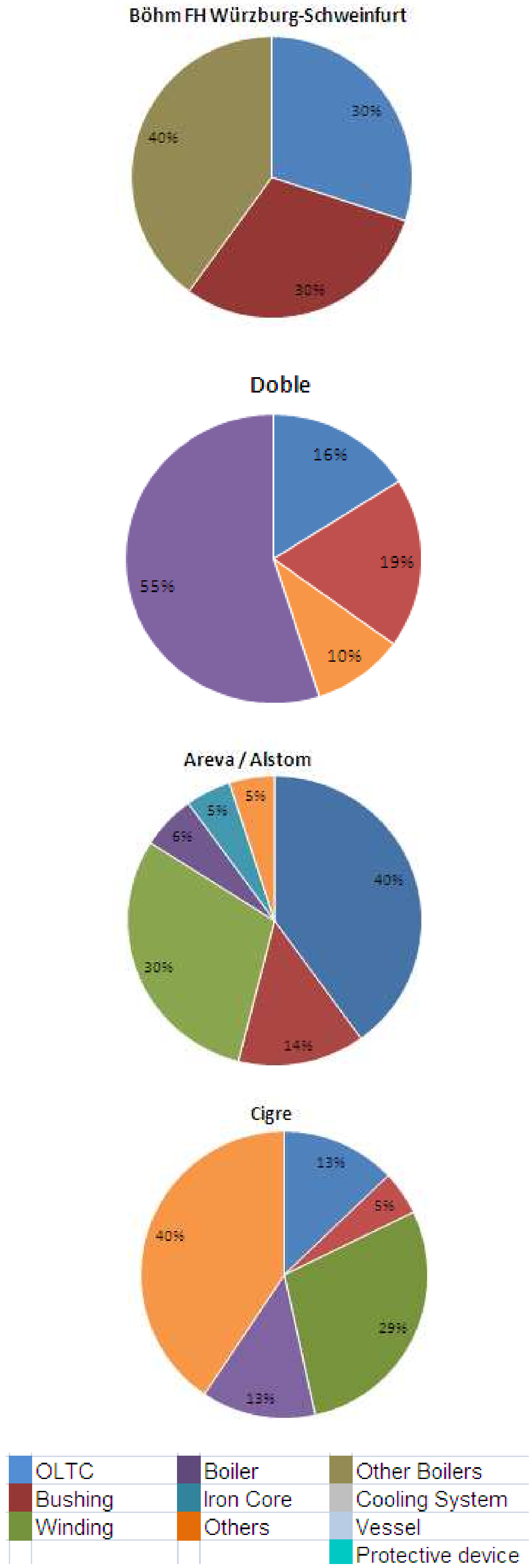

Figure 9. Probability of occurrence of transformer component failures (OLTC=on load tap changers)

Geomagnetic induced solar flare storms follow an 11-year cycle and are expected to peak again in 2013. Particularly in the northern hemisphere, space weather events could severely damage high-voltage transformers.

Thus, it is imperative that the nature of the reliability risk needs to be quantified before a corrective action is developed.

Therefore, vulnerability assessments, equipment testing, operational procedure enhancements and appropriate measures for grid and facility hardening should be considered to address potential impacts.

Actual service life of transformers varies widely depending on the manufacturer, design, quality of assembly, the materials used, quality and frequency of maintenance, and operating conditions.

However, 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. Thus, a proactive strategy for replacing ageing transformers at due time is needed.

This is the reason that in February 2013 two new transformers were delivered to a German nuclear power plant in Lower Saxony. The decision was a precautionary maintenance measure although there were no indications which required an exchange and although the license of this power plant expired on December 31, 2021, according to the German Atomic Energy Act.

In contrast, as a transformer was destroyed by a fire in another plant, the utility decided – in order to safe time - to replace the transformer by an identical spare part of the same age.

However, during the commissioning two years later also this transformer failed and the plant had to be shutdown again. The transformer has been investigated very carefully at a test site but the cause of the failure could finally not be identified.

In parallel, two new transformers were ordered and implemented but the plant was never connected again to the grid and was finally shut down after the Fukushima accident.

References

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

[2] 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.

[3] Berg, H.P. & Fritze, N. (2012). Transformer fires in nuclear power plants – statistics and precautionary measures. *Proc. of the International Colloquium Transformer Research and Asset Management*, Dubrovnik, Croatia.

[4] 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.

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

[6] Bruch, M. et al. (2011). *Power blackout risks, emerging risk initiative – position paper*, CRO Forum, November 2011.

[7] Campbell, R.J. (2012). *Weather-Related Power Outages and Electric System Resiliency.* Congressional Research Service, R42696.

[8] European Committee of Manufacturers of Electrical Machines and Power Electronics – CEMEP (2008). *Uninterruptible power supplies,* European guide.

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

[10] EPRI and USNRC. (2005). *EPRI/NRC-RES Fire PRS 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.

[11] Foata, M. (2010). Transformer fire risk and mitigation. *CIGRE A2 Transformers Session*.

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

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

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

[15] National Infrastructure Advisory Council – NIAC (2010). *A Framework for Establishing Critical Infrastructure Resilience Goals*.

[16] Ng, K.-L.A. (2007). *Risk assessment of transformer fire protection in a typical New Zealand high-rise building*. Thesis, University of Canterbury, Christchurch, New Zealand.

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

[18] Office for Gas and Electricity Markets – OFGEM (2010). *Electricity distribution price control network asset data and performance reporting – regulatory instructions and guidance*, Version 1, May 2010.
[19] Organization for Economic Co-operation and Development - OECD (2012). *Nuclear Energy Agency (NEA): OECD FIRE Database*.
[20] Steindl, E. (2012). Risk management and transformer monitoring. *Presentation at the International Colloquium Transformer Research and Asset Management*, Dubrovnik, Croatia.
[21] United States Department of Energy (2012). *Large power transformers and the U.S. electrical grid*, DOE/OE/ISER, June 2012.
[22] 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.