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RISK AND CONSEQUENCES OF TRANSFORMER EXPLOSIONS AND FIRES IN NUCLEAR POWER PLANTS

RYZYKO I KONSEKWENCJE WYBUCHÓW TRANSFORMATORA I POŻARÓW W ELEKTROWNIACH JĄDROWYCH

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Abstract: *The high failure frequency and the resultant reliability and safety implications in recent years of transformers, in particular at nuclear power plants (NPP), required an in-depth assessment. Fires of main transformers are considered as critical because of the large quantity of oil in contact with high voltage elements. Therefore, these phenomena have been investigated in more detail using the information from the OECD FIRE database for NPP. 12.8 % of all fires and, thus, the most frequent fire source in this database are transformer fires, mainly fires of high voltage oil-filled transformers. Thus, possible diagnostic measures to avoid such events and enhance the reliability currently discussed in Germany are shortly described. Moreover, consequences of transformer failures with respect to a reliable electric power supply are addressed.*

Keywords: *Transformer, nuclear power plants, explosion, fire, reliability, risk management*

Streszczenie*: Wysoka częstotliwość awarii transformatorów, w szczególności w elektrowniach jądrowych (NPP) w oraz wynikające z tego następstwa dla bezpieczeństwa, wymagają dogłębnej oceny. Pożary głównych transformatorów są uważane za awarie krytyczne, gdyż duża ilość oleju ma kontakt w elementami pod wysokim napięciem. Z tego powodu te zjawiska zostały przebadane bardziej szczegółowo z wykorzystaniem informacji z bazy danych ODCE FIRE stworzonej na potrzeby elektrowni jądrowych. Ta baza danych podaje, że przyczyną 12,8% wszystkich pożarów, czyli najczęstszym źródłem ognia, było zapalenie się transformatorów, głównie wysokonapięciowych transformatorów wypełnionych olejem. Z tego powodu w artykule pokrótce opisano omawiane obecnie w Niemczech działania diagnostyczne mające na celu uniknięcie takich wypadków i zwiększenie niezawodności urządzeń. Przedstawiono ponadto skutki awarii transformatorów w odniesieniu do niezawodności zasilania w energię elektryczną.*

Słowa kluczowe: *Transformator, elektrownia jądrowa, wybuch, pożar, niezawodność, zarządzanie ryzykiem*

1. Introduction

A broad spectrum of events such as design defects, voltage surges, lightning strikes, structural damage, a rapid unexpected deterioration of insulation, sabotage, and even maintenance errors can lead to transformer fires and explosions. Experience has shown that the consequences of such events can be severe.

In particular, a fire of an oil-cooled transformer that contains several thousand litres of combustible insulating oil can result in severe damage to nearby power plant structural components such as concrete walls and damage or destroy electrical components such as nearby transformers, bus work, and circuit breakers. A one-year research project led to the discovery of 730 transformer explosions in the USA only [1].

Many experts anticipate that the transformer failure rate will increase significantly in the near future to 0.02 per year. In addition, the shorter lifetime of new transformers will sharply increase the number of failures above this rate after 2010. As about 115 000 large transformers are in operation in the U.S. and about 400 000 worldwide, the number of impacted transformers is high, even if fire and explosion lead to a total damage with a low probability [2].

Power transformers with an upper voltage of more than 100kV 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 [3].

Electric power is normally generated in a power station at 11 to 25kV. 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. 750kV, 400kV, 220kV or 110kV as necessary. 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 26kV, 33kV or 69kV, 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 11kV for load points through a distribution network lines. Finally, the transmission voltage is reduced to the level adapted for household use, i.e. 415V (3-phase) or 240V (1-phase) at distribution substations adjacent to the residential, commercial and small to medium industrial customers. 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 [4].

The major components of a transformer are the coils (windings), the core, the tank or casing, the radiator, and the bushings as shown in Figure 2. Generally, transformer coils are made of copper, because it has a lower resistance and is more efficient compared to other metals.

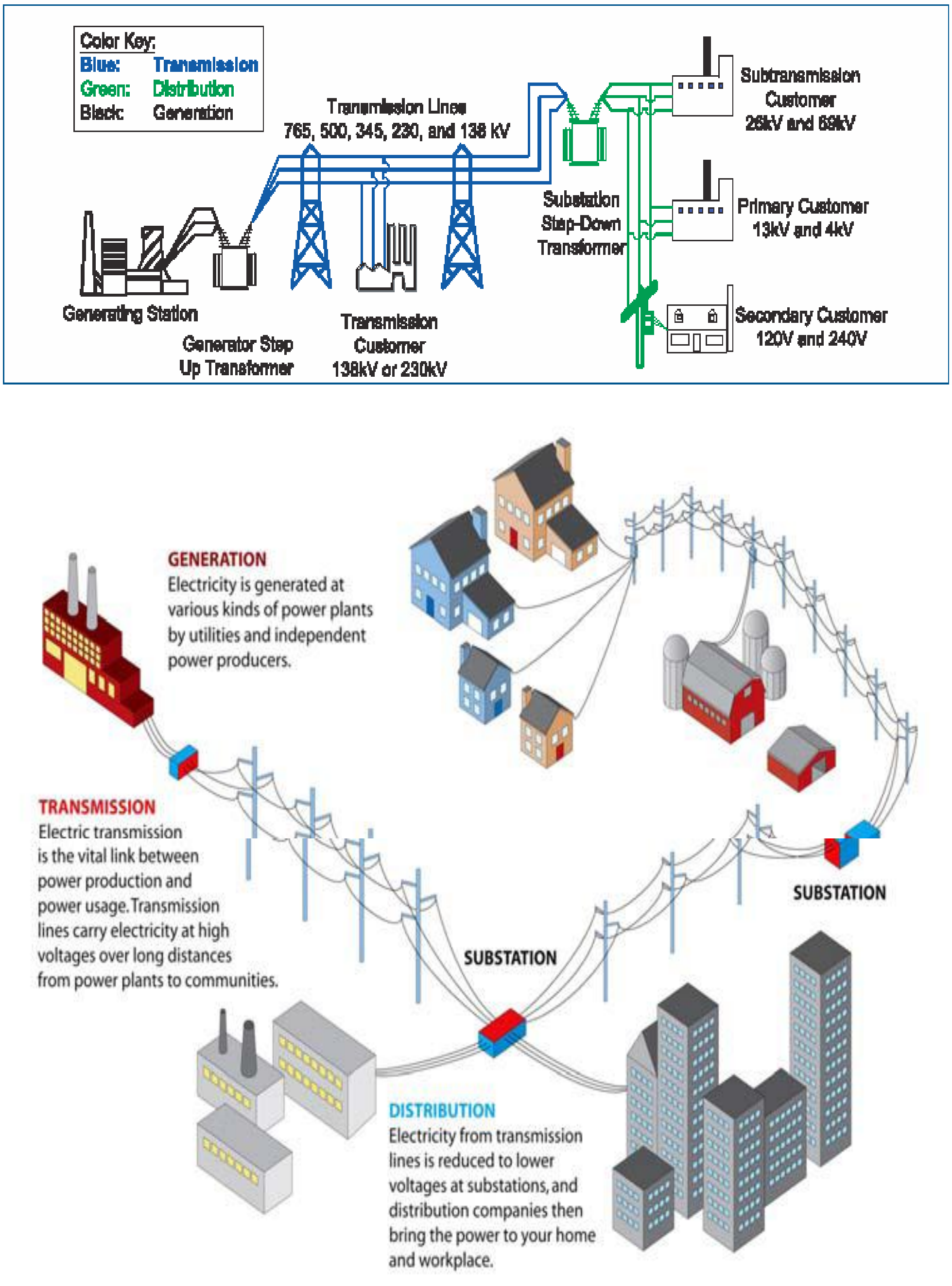

Fig. 1. Typical electrical power network.

Each winding is wrapped with an insulating material such as paper. The primary winding is usually wound around the transformer core and the secondary winding is then wound on top of the primary winding. Between each layer of the windings, another layer of insulating material is wrapped to provide extra insulation between the windings.

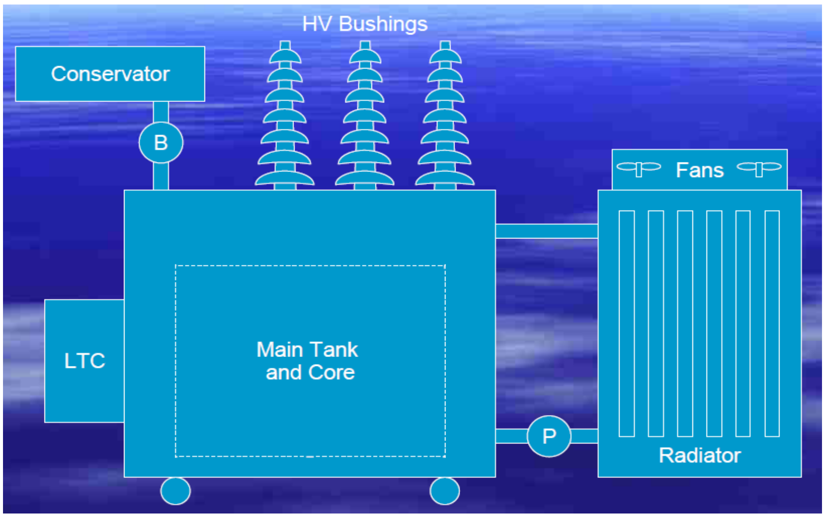

Fig. 2. Main transformer components.

2. Analysis of International Experience

Fire hazard analyses and probabilistic safety assessments of nuclear power plants have shown that fire may be an important contributor to core damage and plant damage states, in particular for nuclear power plants built to earlier standards. Yet, a realistic modelling of fire scenarios is difficult due to the scarcity of reliable quantitative data for fire risk analysis. Therefore, it has been recognized highly important to establish an international fire analysis database. In consequence, several member countries of the Nuclear Energy Agency (NEA) of the OECD have decided in 2003 to establish the International Fire Data Exchange Project (OECD FIRE) to encourage multilateral co-operation in the collection and analysis of data related to fire events at nuclear power plants.
Fire events considered in the OECD FIRE Database are defined as follows [5]:

a) Any process of combustion characterized by the emission of heat accompanied by (open) flame or smoke or both.
b) Rapid combustion spreading in an uncontrolled manner in time and space.

Each OECD FIRE event is described by the narrative event description and a number of coded descriptive fields with attributes selectable from predefined menus. The source of information normally is the narrative event description; the entries in specific coded fields are derived from the narrative event description in order to enable a quick search for specific questions. Detailed results of the first two phases of the project are provided in [6], first results regarding transformer fires are also described in [7].

Currently, records for 415 fire events from nuclear power plants in 12 of the OCED/NEA member countries are included in the OECD FIRE Database [5]. This database provides a reasonable source of qualitative and quantitative information, e.g., on location, affected component, process and event duration. Thus, this database has been analyzed with respect to transformer fire events for high, medium and low voltage transformers. However, it should be mentioned that the criteria for reporting events are different in the OECD member countries. Some countries like Canada, Finland and Sweden are able to report each fire event; others like Germany, France and the United States do report fires only in case of relevance for nuclear safety (e.g. complete loss of off-site power) or additional criteria like duration time of the fire.

High-voltage power transformers (voltage > 50kV) are typically installed in the yard (outside technical buildings). They include plant output power transformers, auxiliary-shutdown transformers, and start-up transformers, etc.

The fires in high voltage transformers are distinguished in catastrophic and non-catastrophic failures which are defined and coded separately in OECD FIRE Database in the following way:

a) The 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.
b) Similar to the “catastrophic” code, the non-catastrophic code includes the high voltage power transformers typically installed in the yard. This code shall be used for fires which do not involve a rupture of the transformer tank, oil spill and burning of oil spattered at a distance from the transformer.

Medium or low voltage (voltage level < 50kV) transformers include all transformers that are not integral parts of another equipment. Control power transformers and other small transformers, which are sub-components in electrical equipment, should be ignored. They are assumed to be an integral part of the larger component. Examples of transformers accounted for in this code include 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 compared to high-voltage transformers.

Among the reported 415 fire events, transformers are the most frequent fire source with in total 53 events representing an amount of 12.8 % of all fires in the OECD FIRE Database. Most of them are fires of high voltage (oil-filled) transformers and the majority of these transformer fires have to be classified as catastrophic as shown in Figure 3. Moreover, 18 of the transformer fires are resulting from a high energy arcing fault which again represents the highest percentage of all components impacted by this cause. Examples of transformer fires are described in [8].

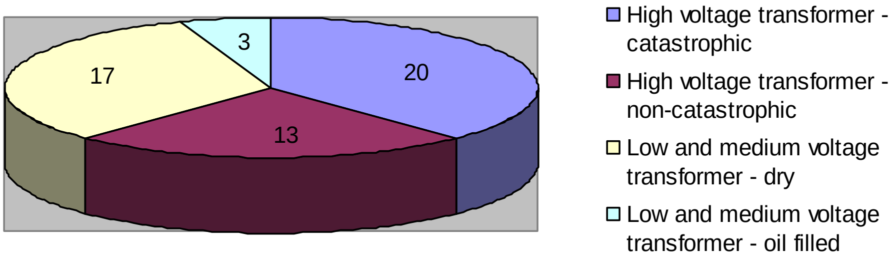

Fig. 3. Transformer fires.

Although the large oil-filled transformers are not considered as nuclear safety equipment, the failure of a large transformer at power usually results in a reactor trip and may complicate efforts to maintain the reactor in a safe shutdown condition.
35 of the 53 fire events occurred during full power operational states. 15 events were observed during the start-up mode of the nuclear power plant or in the shutdown state. In three cases the operation mode is unknown; this is due to the fact that the information on fire events earlier than 1990 is sometimes very short or incomplete.
The majority of transformer fires as listed in Table 1 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). All 33 fires have originated at the transformer itself.

Table 1. Transformer fires – area where the fire started.

Area	**Transformer type**		
	HV oil-filled	MV or LV oil-filled	MV or LV dry
Switchyard	8	-	2
Reactor Building	-	-	4
Electrical Building	2	1	4
Turbine Building	-	-	1
Auxiliary Building	-	-	4
Transformer yard/outside	23	2	-
unknown		-	2
Total	**33**	**3**	**17**

20 of the fires were observed at dry medium voltage or low voltage transformers, only three of these fires were found at oil-filled transformers. The remaining 17 fires mainly occurred at transformers in process rooms, rooms with electrical control equipment and switchgear rooms, which are mainly located in the technical buildings listed before. The low number of oil-filled medium or low voltage transformer fire events results from the fact that in the majority dry transformers are installed.

Only very few transformer fire events lead to severe consequences, one of these resulted in a complete loss of off-site power, and four events lead to the total loss of one safety train. In all cases no safety significant consequences occur.

As outlined in Figure 4 half of the transformer fires could be suppressed successfully within 30 minutes, only 3 fires (of oil-filled high voltage transformers) lasted more than three hours. In 9 cases the duration of the transformer fires is unknown, some of them may have also lasted more than 180 min. Three fires with unknown duration time were self-extinguishing, two high voltage transformers (non-catastrophic) and one dry medium or low voltage transformer.

In practice, the number of transformer fires may be higher than reported in the OECD Database, due to the applied reporting criteria in member countries. Anyway, the finding that the majority of fires are suppressed successfully within 30 minutes will be confirmed, because in one country only those fires have to be reported for which the duration is longer than 30 minutes.

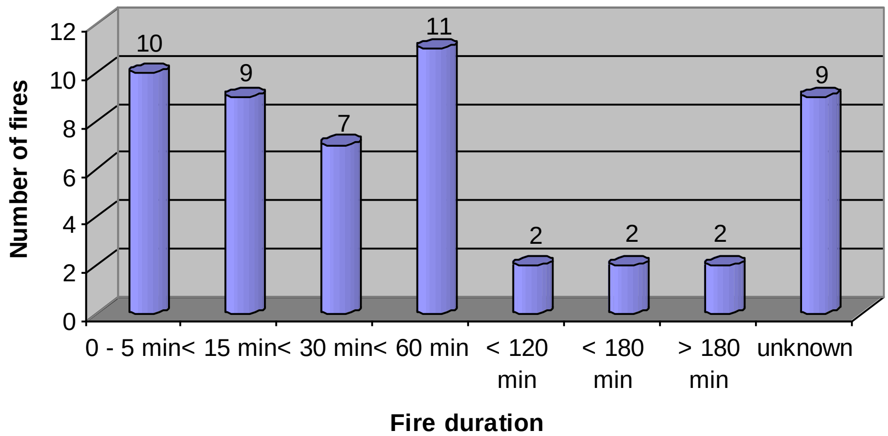

Fig. 4. Duration of transformer fires.

3. Possible Precautionary Measures

Licensee maintenance and monitoring programmes are generally structured around available industry recommendations and operating experience looking at typical parameters like oil temperature and levels. Currently, the German Reactor Safety Commission, an advisory body of the Federal Ministry for Environment, Nature Conservation and Reactor Safety, discusses in detail appropriate test and monitoring programmes for oil-paper isolated and dry transformers in German nuclear power plants. Major aspects are the precautionary measures, implementation of more standardized test procedures, the role of ageing in case of a transformer with operating time longer than 25 years due to a slightly higher failure rate.

A large number of transformers installed in German nuclear power plants, especially in the medium power range, has already a long operating life, so that further damages of the transformer can not be excluded.

With increasing age of nuclear power plants and thus of the transformers, especially of the generator transformers, which have a higher load than for example the emergency power transformers, a relative failure increase was observed. In the years 2007, 2009 and 2011 in northern German plants three generator transformers failures have occurred, one resulting in a fire.

Although in the cases referred to there were indications that aging was the cause of failure, the end of life time can not be derived from the measurements performed on the transformers.

Reported failures were related to both transformers with operating age of 25 to 30 years and newly installed transformers. A reliable data base on measured results, from which specific aging phenomena and failure rates can be derived, is not available. Therefore, a replacement of transformers as a precautionary measure cannot be recommended.

The VGB test plan for oil-paper insulated transformers has been implemented from 01.12.2009 in all German nuclear power plants. This unified test plan for all systems is defined in a VGB guideline [9]. This programme includes a minimum level of repeat tests to be conducted at specified intervals on generator transformers, transformers for own consumption, standby power and emergency power transformers. This concept for monitoring transformers in nuclear power plants will be updated in the future based on lessons learned in all German nuclear power plants.

4. Safety of Critical Infrastructure

In addition to the 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 it could be difficult to quickly replace it. Such failures could be caused, e.g., by external hazards. 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 [10]. The underlying methodology described in [10] as a whole is illustrated by a case study based on a sample from a population of over 400 extra high voltage power transformers.

The limited availability of [spare] extra-high-voltage transformers in crisis situations presents potential supply chain vulnerability [11].

Thus, as a key component of power grids, transformers deserve special attention. An alarming analysis shows that many power transformers used in the electricity supply are old and could cause major losses in the coming years [12].

5. Concluding Remarks

The risk assessment for transformers covers an analysis of all possible causes for failures and the resulting consequences. Possible precautions to limit the risk include protective devices, design measures and testing. The severity of a failure will be high in case external phenomena may occur which could be dangerous for people or installations. Particularly explosion resulting in a fire is of great concern and importance.

Many events in all types of power plants and substations (see Figure 1) have shown that ageing of transformers might be a matter of concern. Thus, transformer age might be an important factor to consider when identifying candidates for replacement or rehabilitation. This aspect is not only relevant for nuclear power plants but also for conventional plants generating electricity. In the future, also the reliability of transformers in wind turbines has to be assessed.

Age is one important indicator of remaining life and upgrade potential to current state-of-the art materials. During transformer life, structural strength and insulating properties of materials used for support and electrical insulation (especially paper) deteriorate. Ageing reduces both mechanical and dielectric strength. All transformers are subject to faults with high radial and compressive forces. Clamping and isolation can then not longer withstand short circuit forces which can result in explosions and fires.

A further important task for receiving the required risk informed insights is to compare the distinguishing parameters of transformers such as their insulation type, number of phases, adjustability, core/coil configuration and winding configurations, oil content, design against overpressure, maintenance and monitoring features. In addition, the fire extinguishing systems installed in the locations of transformers have to be considered which may also affect the fire duration. Such investigations are intended in the future. For that purpose, exemplary experiences are also helpful.

Moreover, one result provided in [13] shows a correlation between the fire rate per year and the voltage which depicts an increasing probability for a transformer failure resulting in a fire for larger power transformers as illustrated in Figure 5.

The statistical analysis indicates a potential for reducing the fire risk and limiting the consequences of the fires mainly for high voltage on the one hand by reducing the oil fire loads and, on the other hand by further increasing the electrical

protection means decreasing the ignition probability by reducing the risk by prevention of high energy electric arcing, etc.
Furthermore, there are some indications that ageing may play a non-negligible role with respect to electric failures resulting in fires or explosions of transformers. However, one major problem is the lack of a reliable and transparent database describing which component is the faultiest one. As explained in [14] seven different databases show a very diverging picture of root causes. Therefore, additional investigations and research are needed in this field for developing a useful database for improving safety and reliability.

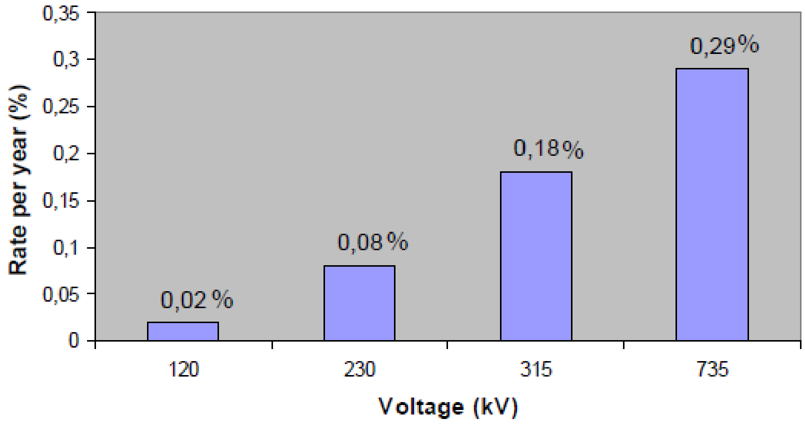

Fig. 5. Fire probability vs. voltage.

Although actual service life varies widely depending on the manufacturer, design, quality of assembly, materials used, maintenance, and operating conditions, the designed life of a transformer is about 40 years, but in practice industry has noted that they last 20 to 30 years. Thus, a clear strategy for replacing ageing transformers at due time because ageing transformers are a risk to the electricity supply.
A way to get an overall impression of the state of the total transformer population, statistical failure analysis can be performed. The failures reported the last years are used as input for the analysis. In this paper the analysis will be discussed starting by showing the population now in service. This population can be split up in two sub-populations based on the voltage level (and power rating) of the transformers. The reported failures are also discussed and also the failures can be divided into sub-groups based on the type of failures reported [15]. The failure data together with the populations in service are used to perform statistical analysis. From the analysis it can be seen whether failures occur in relation to the age of the transformers (ageing).
The general approach is graphically presented in Figure 6.

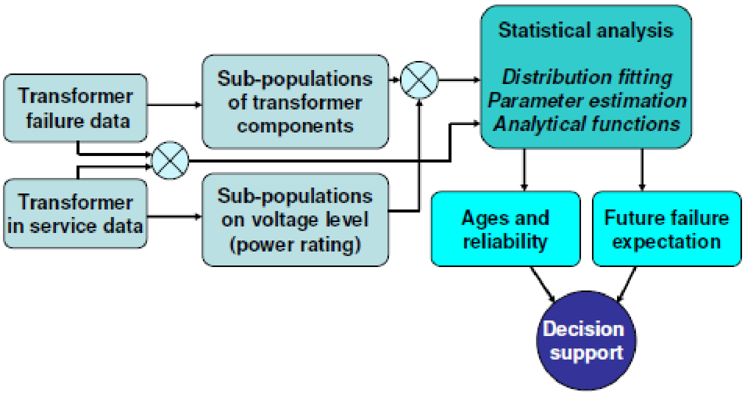

Fig. 6. Approach of the analysis on power transformers.

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