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Power plant transformer explosion and fire

Keywords

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Abstract

The transformer is the key equipment for electric power transmission. It has been found that main transformer failures require an in-depth assessment because of the high failure frequency and the resultant reliability and safety implications. Transformers are considered as a critical equipment because of the large quantity of oil in contact with high voltage elements. In particular, experience has shown an increasing number of transformer explosions and fires in all types of power plants worldwide. Therefore, these phenomena have been investigated and are discussed in more detail in this paper with regard to causes for these events, potential influence of the age of the transformers and possible diagnostic measure in order to avoid such events. For that purpose different types of databases have been evaluated.

1. Introduction

Events such as design defects, voltage surges, lightning strikes, structural damage, rapid unexpected deterioration of insulation, sabotage, and even maintenance errors can and do lead to transformer fires and explosions and the consequences can be severe.

A fire of an oil-cooled transformer that involves 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 [12].

A one-year research project led to the discovery of 730 transformer explosions in the USA only. 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 after 2010.

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 [5].

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 [14].

Electric power is normally generated in a power station at 11 to 25kV. In order for the transmission lines to carry the electricity efficiently over long distances, the low generator voltage is increased to a higher transmission voltage by a step-up transformer, i.e. 400kV, 220kV or 110kV as necessary. Supported by tall metal towers, lines transporting these voltages can run into hundreds of kilometres. The grid voltage is then reduced to a sub-transmission voltage, typically 33kV or 66kV, in terminal stations (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.

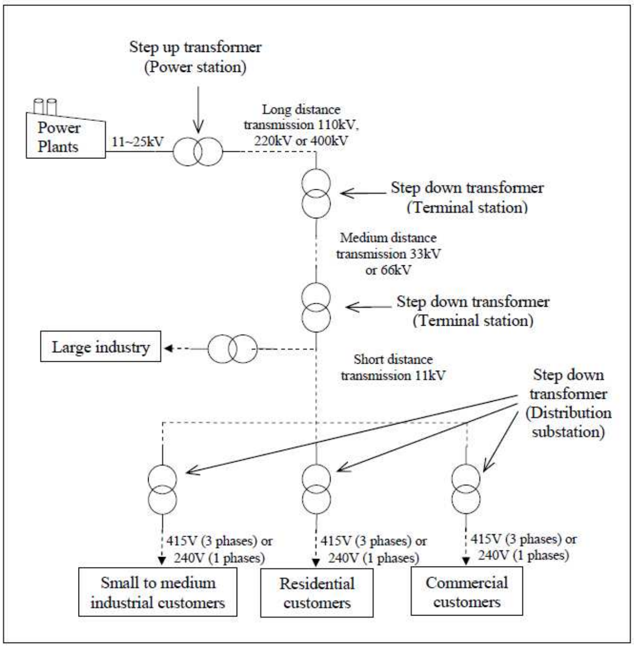

Figure 1. Typical electrical power network

Currently, three following types of transformers are commonly used:

(1) dry type transformers,

(2) less flammable liquid insulated transformers and

(3) flammable liquid insulated transformers.

Dry type transformers are transformers containing solid or gas insulation material. The fire hazard of dry type transformers is generally considered to be low compared to liquid type transformers due to the limited amount of combustible materials present in the transformers.

For liquid type transformers, less flammable liquid is expected to have a high fire point (above 300°C) and hence, is more difficult to ignite. From a fire hazard point of view, transformers insulated with flammable liquid is considered to have the highest fire hazard out of the three types of transformers due to the combustible liquid oil present and their relatively lower fire point (100°C to 170°C).

2. Geometry of a transformer

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. 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.

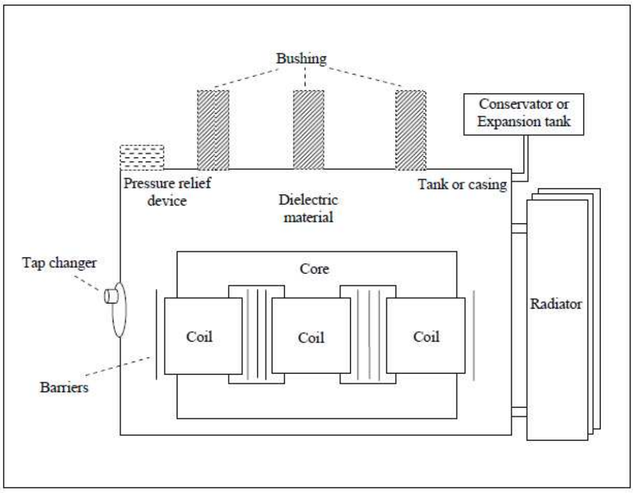

Figure 2. Schematic drawing of typical transformer according to [7]

The major transformer components are briefly described below:

1) Core is a ferromagnetic material (commonly soft iron or laminated steel) that provides a path of high magnetic permeability from the primary circuit to the secondary circuit.

2) Windings allow a secondary voltage to be induced in the secondary circuit from the alternating current (AC) voltage in the primary circuit. The change in magnetic field in the transformer core caused by applying primary AC voltage causes an induced magnetic field and, hence, voltage on the secondary winding.

3) Tank or casing, which is usually a reinforced rectangular structure in these transformers, contains the dielectric material, the core and the windings.

4) Dielectric material is a substance that is a poor conductor of electricity but an efficient supporter of electrostatic fields. It can be fluid oils, dry solids or gases.

5) The expansion tank or conservator containing dry air or dry inert gas is maintained above the fluid level.

6) Bushing is an insulating structure that provides a conducting path though its centre, its primary function is to insulate the entrance for an energised conductor into the tank.

7) Pressboard barriers, between the coils and between the coils and core, are installed to increase the dielectric integrity of the transformer.

8) The tap changer is a connection point along a transformer winding that allows the number of turns to be selected, or so-called voltage regulating device.
9) The radiator provides a heat transfer path to dissipate the internal heat generated in the transformer.
10) The pressure relief device is used to protect the tank against excessive pressure release inside a transformer tank.
An oil transformer is made up of a steel tank, which includes windings and the transformer's iron core. During the manufacturing phase, the windings are covered with insulation paper and electrical insulating board. The steel tank is full of transformer oil and it impregnates the insulation paper, during which time the combination of paper and oil and the electrical insulating board form a necessary electrical insulation. To ensure that the transformer can operate without failure for at least 30 years and that the life expectancy of the transformer can be correctly estimated the properties of the transformer oil and insulating paper must be kept at a specific level.

3. Results from international databases

One application of the OECD FIRE Database has been an analysis of events associated with explosions [4]. A query in the Database on the potential combinations of fire and explosion events has indicated a significant number of explosion induced fires. Most of such event combinations occurred at transformers on-site, but outside of the NPP buildings or in compartments with electrical equipment. Approximately 50 % of the fires were extinguished in the early (incipient) fire phase before the fire had fully developed. As a consequence of these indications, improvements concerning the fire protection of transformers are intended in Germany. As there is no specific coded field in the database to indicate explosions, the main source of information is provided by the event description field. The 22 reported explosions amount to 6.4 % of all events reported up to date (see *Figure 3*).
Concerning the process of explosion distinction should be made between an explosion as a process of rapid combustion (chemical explosion) and an explosion as a physical process resulting from a sudden gas pressure rise by a high energy electric (arcing) fault (HEAF).
A chemical explosion was found for only three events (solvent vapor, diesel fuel, hydrogen). In the other 18 cases, HEAF events obviously took place at the same time indicating a physical explosion. In some of these cases the electric fault might have caused a fuel pyrolysis or fuel spread and acted as an ignition source for a chemical explosion, thus a HEAF event and a chemical explosion may have taken place simultaneously.

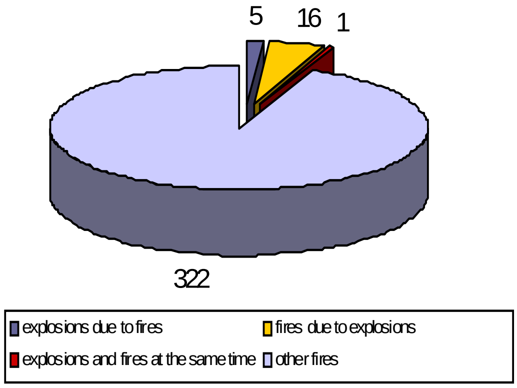

Figure 3. Results from the OECD FIRE Database

In one event, a fire led to the explosion of diesel fuel vapor while in another event a fire and an explosion occurred independently from each other in parallel. In all other cases explosions induced the fire [3].
Concerning the buildings/locations where the events took place it was found that 13 (59 %) events took place outside buildings, three inside electrical buildings.
A majority of 59 % of the reported explosions (again 13 events) started at transformers. The other 9 events took place at electrical cabinets, other electrical equipment, or process equipment (3 each representing 14 %). External fire brigades were needed in 4 of 22 cases (18 %). The 22 events were also evaluated concerning the fire duration with the following results shown in *Table 1* [3]:

Table 1. Fire duration

Fire duration	Number of events
0 - < 5 min	11
15 - < 30 min	3
30 - < 60 min	3
> 60 min	3

For the remaining two events no information on the fire duration is provided. This is in good agreement with the fire durations recorded for all events, where for approx. 55 % of the events (128 out of 233 events with fire duration provided) a fire duration of less than 15 min could be found.

As one can see from *Figure 4*, fires of high voltage transformers contribute to about 8 % of all fires contained in the OECD FIRE database.

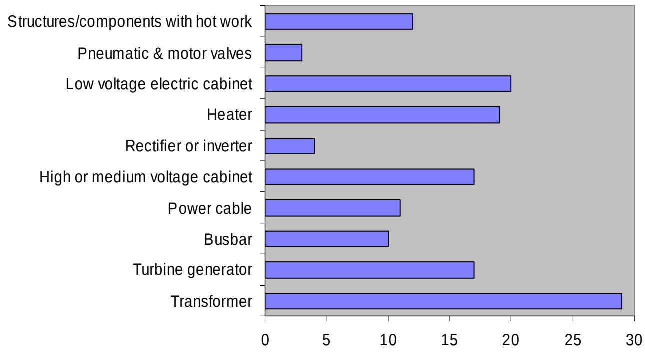

Figure 4. Components where the fire started

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.

Although transformer fire occur frequently, the public interest increases when such a fire takes place in a nuclear power plant. In August 2008, a fire in the main transformer of unit 2 of the Diablo Canyon Nuclear Power Plant started, it was the fifth comparable event in 25 years (see Figure 5) in the plant which starts operation in 1985 (Unit 1) and 1986 (Unit 2).

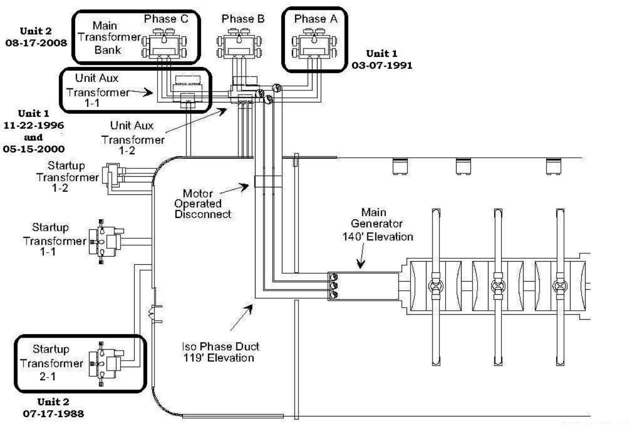

Figure 5. Transformer fires in Diablo Canyon NPP

4. Transformer fire in a German nuclear power plant

A short circuit led to a fire in one of the two generator transformers. The short circuit was recognised by the differential protection of the generator transformer, and the circuit-breaker between the 380-kV grid connection and the affected generator transformer as well as the 27 kV generator circuit-breaker of the unaffected transformer were opened.

At the same time, de-excitation of the generator was actuated. The short circuit was thereby isolated. In addition, two of the four station service supply busbars were switched to the 110-kV standby grid. Within 500 ms, the generator protection system (initiating 'generator distance relay' by remaining current during de-excitation of the generator which still feeds the shot circuit) caused the second circuit-breaker between the 380-kV grid connection and the intact generator transformer to open. Subsequently the two other station service supply busbars were also switched to the standby grid. After approx. 1.7 s, station service supply was re-established by the standby grid. Due to the short low voltage signalisation on station service supply busbars the reactor protection system triggered according to the specifications a reactor trip.

After the switch to the standby grid, feed water pump 2 was started automatically. After about 4 s it stopped injecting into the reactor pressure vessel and subsequently was switched off again. This caused the coolant level in the reactor pressure vessel to drop so that after about 10 min the reactor protection system actuated steam line isolation as well as the start-up of the reactor core isolation cooling system. About 4 min after the actuation of steam line isolation, two safety and relief valves were opened manually for about 4 min. This caused the pressure in the reactor to drop from 65 bar to about 20 bar.

As a result of the flow of steam into the pressure suppression pool, the coolant level in the reactor pressure vessel dropped further. After closing the safety and relief valves the level of reactor coolant decreased further because of the collapse of steam bubbles inside the reactor pressure vessel.

Thereby the limit for starting the high-pressure coolant injection system with 50% feed rate was reached and the system was started up by the reactor protection system. Subsequently, the coolant level in the reactor pressure vessel rose to 14.07 m within 6 min.

The reactor core isolation cooling system was then automatically switched off, followed by the automatic switch-over of the high-pressure coolant injection system to minimum flow operation. Subsequent reactor pressure vessel feeding was carried out by means of the control rod flushing water and the seal water.

Due to the damage caused by the fire in the transformer, the plant was shutdown. The transformer was located 50 m from the reactor building.

The transformer fire shows the normal behaviour of a big oil-filled transformer housing, the fire lacks combustion air and produces a large amount of smoke (see *Figure 6*). All fire fighting equipment worked as designed. Because of the non chloric oil the influence on the environment is low.
The fire extinguishing activities start with an automatic fire extinguishing system, followed by activities of the on-site fire brigade, later supported by external local fire fighters (see *Figure 7*).

Figure 6. Development of fire in a transformer

After the end of the fire fighting operations, a foam attack and later a flooding of the transformer vessel has been started to cool down the spools.
The time, until the fire in the transformer housing was extinguished, lasted nearly seven hours, approx. 70.000 kg transformer oil were ignited.
The long duration of the extinguishing phase is due to the large amount of fire loads involved and the exceptional heat capacity of the transformer core and windings (approx. 350.000 kg of iron and copper).

Figure 7. Extinguishing activities

5. An example of simulation of the causes of a transformer fire

The purpose of the simulation was to a coupling of electromagnetic, thermal and take into account hydrodynamic phenomena. Therefore one has to:

- determine the magnetic field created by the inductance and/or arc in the surrounding field versus the injected current per phase;
- calculate the induced currents and the Joule and Eddy current local dissipated power;
- calculate the temperature by using the resulting above values as heat sources.

The calculation is done using four sub models as described in [9] and [10]. The first equation which has to be solved is magneto-dynamic:

$$r\vec{o}t\left(v, r\vec{o}t\vec{A}\right) = \mu_0 \ \vec{J}_{source} \tag{1}$$

It derives from the Maxwell equations, which rule the overall electromagnetic phenomena.
The magnetic field is expressed through the potential vector:

$$\vec{B} = r\vec{o}t\vec{A} \tag{2}$$

The thermal sub model resolves the partial derivative equations in a Cartesian geometry and is the following:

$$\rho C_p \frac{\partial T}{\partial t} + pC_p VgradT + div\left(-KgradT\right) = Qth \tag{3}$$

Diffusion term (Transient) — Convection term — Conduction term (steady)

Where:

ρ	: Volume mass
C_p	: Heat capacity
V	: Speed vector
K	: Heat conductivity
Qth	: Heat sources density

The hydrodynamic sub model resolves the Navier-Stokes equations and mass conservation equations as:

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho\left(\vec{v} \cdot \vec{\nabla}\right)\vec{v} \cdot \overline{\sigma} = \rho\vec{g} \tag{4}$$

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \rho\vec{v} = 0 \tag{5}$$

The kinetic sub model is ruled by the Arrhenius Law:

$$k = A \cdot e \frac{E_a}{R,T} \qquad (6)$$

Where:
A : Pre-exponential factor
E_a : Activation energy
R : Perfect gas constant
T : Temperature
k : Constant expressing the quickness of the reaction

For the pre-exponential factor of the expressed Arrhenius Law experimental data have been used. These data have to be gathered according to the type of gas and associated activation energy:

- The oil-gas composition is identified for every temperature,
- The different element concentration versus time and temperature in mineral oil environment is known.

Calculations were conducted with the hypothesis of forced and directed oil circulation as in [9]. The magnetic core was made free in temperature.
Before simulating the disruptive failure in the transformer, the steady state was simulated in order to obtain a basis for the rest of the calculation. The steady state calculation enables to observe the transformer behaviour under nominal electrical load. It corresponds to the normal transformer operation at normal temperature and pressure levels.
The electrical arc is simulated in the transient state by inserting a copper wire fed by the assumed currents. Once the wire reaches the temperature of electrical arcing, oil cracking process, gas production and pressure rise increase severely.
The electrical arc is a high temperature plasma. At this heat level, the oil cracking process generates sufficient gas to create the overpressure. The vessel maximum tolerated pressure was determined to be more than 1 bar above atmospheric pressure, but the pressure relief valves are inefficient for such pressures.
The pressure gradients versus current faults are of utmost importance, as they explain transformer explosion due to the inadequate in-service instrumentation or devices.

6. Concluding remarks and outlook

6.1 Further investigation

It has been found that main transformer failures require an in-depth assessment because of the high failure frequency and the resultant reliability and safety implications [13].
A lot of events in all types of power plants and substations has shown that ageing transformers are a matter of concern. Thus, transformer age might be an important factor to consider when identifying candidates for replacement or rehabilitation. 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 [11]. 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.
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.
However, the transformer which burnt 2008 in Diablo Canyon was only 9 years old.
In 2003, the International Association of Engineering Insurers (IMIA) presented a research, which contained an analysis of transformer failures, which have occurred in IMIA member countries (see [1] and [2]). During the period 1997 – 2001 a total of 94 failures occurred.
These 94 failures have been divided in *Table 1* below according to age.

Table 2. Division of failure according to age of transformer 1997 – 2001

Age	Number of failures
0 – 5 years	9
6 – 10 years	6
11 – 15 years	9
16 – 20 years	9
21 – 25 years	10
Over 25 years	16
Age unknown	35

Insulation failures were the leading cause of failure in this study. The average age of the transformers that failed due to insulation was 18 years, in some cases leading to transformer fire and explosion.
During the normal use of a transformer, oil and insulation paper becomes old and at some phase

they are no longer able to fulfil their tasks concerning electrical and mechanical strength.

The damage databases provide clear observations that transformer damages often arise due to defects in insulation that originate in the interior of the transformer. It is, therefore, necessary to monitor the ageing phenomena so that reliable information concerning potential faults can be obtained during the earliest phase possible.

The most reliable method for obtaining this information is to take oil samples from the transformer oil and carry out a so called Dissolved Gas Analysis. Certain gases are formed in transformer oil as a result of the transformer's age but they are also formed as a result of different over-loading situations, partial discharges and electric arc phenomena, etc. This method will now implemented in several nuclear power plants to avoid recurrence of a fire event.

6.2 Countermeasures

Protecting transformers against explosion and fire has become a priority because

- Worldwide privatization programs of electricity production and distribution companies have resulted in a reduction of investments,
- Today's competitive markets demand longer life, greater production, which results in ageing equipment and overloaded transformers.

However, transformer failures and transformer fires are not only important for operational reasons but could lead to significant safety-relevant consequences. Therefore, a working group of the International Council of Large Electric Systems was initiated in 2007 which deals with transformer fire safety practices. Results of this working group are expected at the end of 2010.

Detection techniques serve as a warning system to developing abnormalities in a transformer or one of its components. Detection techniques are comprised of parametric measurements and visual inspection.

The parametric measurements most often used are the current, the voltage, the internal pressure of the tank, the oil level, the oil and winding temperature, gas in oil analysis, and winding power factor, to name a few. The least frequently used measurements include the load tap changer acoustic vibration, acoustic surveillance of partial discharge, etc.

Visual inspection of the transformer exterior reveals important condition information. For example, valves positioned incorrectly, plugged radiators, stuck temperature indicators and level gauges, and noisy oil pumps or fans. Oil leaks can often be seen which may indicate a potential for oil contamination, loss of insulation, or even environmental problems. Physical inspection requires staff onsite experienced in these techniques.

Existing diagnosis concepts for power transformers are traditionally categorized by the underlying measurement technique (online vs. offline). The sub division into physical subsystems (e.g. mechanic subsystem, dielectric subsystem, thermal subsystem) is a first step for a model-based approach. Interpretation methods for measurement results and the integration of the subsystems into a common diagnosis scheme are missing links on the way to a model-based diagnosis concept [6].

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