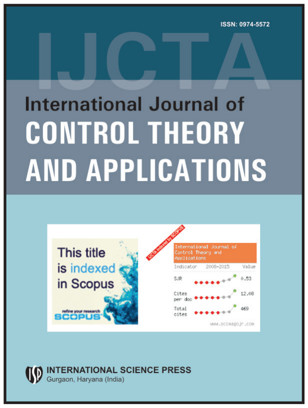

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Power Transformer Fire and Explosion: Causes and Control

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Abstract: An increasing number of failures of power transformers over the world has led to greater interest in building up much needed expertise in electric power transformers, from its design to both preventive and prescribed maintenance. Winding failure is a frequent cause of transformer failure, bushing failure leads of fire and explosion, but it is still uncertain whether the increasing failure of transformers may be related to increasing lightning activity or increasing electric energy of the transient, surge voltages generated by lightning, especially long continuing currents and rate of rise of currents. But there are other important causes as well which need close attention, including wearing out of the contact points of tap changers in power generating and substation transformers, and poor maintenance of transformer oil. This paper seeks to review some of the well-known causes that lead to transformer fire and explosion, and highlights the important parts of the power transformer that need careful selection, installation, maintenance and condition monitoring. Moreover the containment of fires and measures that help to prevent transformer explosions in case of transformer fires are also discussed.

***Keywords*:** Embedded systems, Smart Antenna; Adaptive Array; Artificial Neural Network.

1. INTRODUCTION

Power transformers play a crucial role in electric energy transmission and distribution. The typical layout, cooling and protection systems of an electric power transformer is as shown in Figure 1. Although they age with time as devices that carry large amounts of electric energy for twenty four hours daily throughout the year, they also vulnerable to catching fire and exploding, resulting in major loss of power supply to the consumer and danger to other expensive power equipment in substations, generator stations and other buildings and to human lives [1-2]. This is particular so with oil filled transformers found in generating stations and substations. Transformer condition monitoring and fire risk management are major concerns to power authorities. When such failures of transformers occur the power utility loses its integrity with the government and public, and the consequences are economical as well as environmental including pollution of water supply by the spilt oil. In addition to the failure of energy supply with the collapse of the transformer and the consequent economic loss. The additional consequences includes the shattered bushing ceramic pieces damaging other equipment, buildings and putting people at risk, the pressure built up by the explosion impacting other structures, the leaking insulating oil fire lighting up the combustible materials and structures. Also the heat flux causing failure of electrical and electronic systems, steel structures collapsing due to the heat generated, the fire plume from the burning transformer creating a charged atmosphere under overhead lines leading to flash over and line to ground or line to line faults (Figure 2).

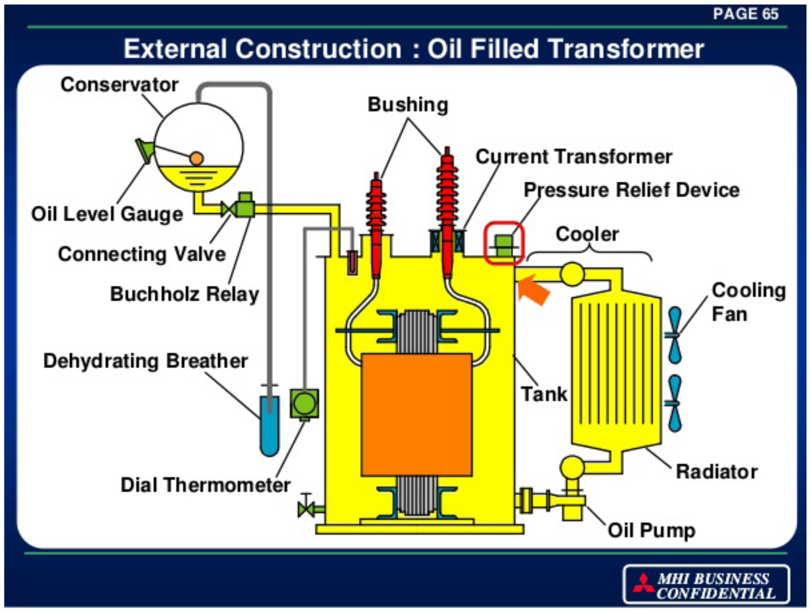

Figure 1: Power Transformer
(http://www.slideshare.net/marimuthusudalaimuth/mhi-transformer)

Figure 2: Fire due to mineral oil from a high voltage transformer
(http://www.nbcrightnow.com/story/14924340/)

Smoke from a burning transformer can ionize under high voltage power lines causing transmission line short circuits. This trip the earth fault relays of the transmission systems. Energized electrical cables with combustible insulating and jacketing material could also catch fire. Amongst the major pieces of equipment that are prone to fire hazard in an electrical substation of generator station are those of the oil insulated transformers, the reactors, the circuit breakers, hydrogen cooled synchronous condensers and the standby diesel generator buildings.

There are three generic methods to prevent the damage in the transformer. The first method is using the alternative liquid insulation such as PCBs, silicon dioxide, high molecular weight oils and synthetic ester. At first, the PCBs were widely used for a small power transformer due to the advantage of the non-burning properties. Then, the PCBs are banned because the releasing of dioxins into the atmosphere when it is burn at high temperature. Another group of fluids does not burn, but it risk the people who carry the situation or in industrial applications. The second method is using the solid insulation in designing the dry-type transformer.

This type of transformer usually installed underground or basement of hotel or shopping centers. The limitation of this method is the voltage operating level of only up to 132kV. The last method eliminates the transformer oil into the gaseous insulation. At the time when the PCBs are banned, the researchers in Europe reconsidered the use SF6 gas as a replacement about three bar gas pressure and use as of additional cooling. This design is successful at the low power rating. Japanese manufactures designed a two-phase transformer using SF6 gas to establish the insulation system and per-chloroethylene fluid to remove the heat from the transformer. The design proved very successful rated at 275kV and are placed into the services. Engineers always considers a lot of alternative design of the transformer but there are a limitation especially the use of alternative fluids and solid insulation. The gaseous insulation using SF6 is a successful design of the transformer because it is used in critical or strategic substations. This design is generally not be subject to the fire hazards or explosions. In spite of the prevalent use of transformers and the need to be constantly alert to their condition and regular maintenance, it remains a power device that is least understood and poorly managed amongst the high voltage equipment found in power system network. In this paper, the authors attempt to review some of the major monitoring and maintenance issues related to the power transformer and the causes and solutions to transformer fire and explosions.

2. CASE STUDIES ON TRANSFORMER FIRES AND EXPLOSIONS

Over a period of a year out of it is found on an average eight in one thousand distribution transformers is expected to fail with 30% of it due to lightning related causes. The lightning parameters directly related to transformer failures are high return stroke peak current, high rates of current rise, multiple flashes and positive lightning flashes. With aging transformers, with reduced insulation strengths, lightning flashes accelerate the end of life failures [3]. Lightning flashes to the customer electrical installations impact the transformers through the secondary windings, as well as lightning currents in neutrals and secondary circuits. With distribution transformers, about four percent of the fuses operate each year due to various causes. Each year half a percent of the fuses put in action due to lightning related causes. The majority of fuse operations (about 65 percent) occur in conjunction with lightning caused circuit breaker operation. Frequently the transformers saturate during the prolonged lightning return stroke currents and continuing currents, resulting in low impedance faults. The 35% percent or so high impedance faults (where the circuit breaker was not tripped due to relatively low fault currents) are probably due to faults in the secondary (customer side) of the transformer. The faults on the secondary side of the transformers are due to direct lightning strikes to low voltage lines, induced surge voltages by distant lighting strikes and lightning strikes to buildings being coupled to the low voltage power line.

Causes of transformer failure that lead to fire and explosion include the following [4-5]:

- Inter-turn insulation failure due to mechanical damage during manufacture, infiltration of water, long term overload and over voltages, mechanical movements of turns and obstruction in oil flow.

- Water contents in oil, sludge in oil, or in the insulation between tank and winding leading to winding-tank insulator failure.
- Thermal faults caused by overloading of transformer, poor connections at bolted connections with cables or draw rod of bushings, or poor oil flow inside the transformer [6].
- Partial discharges may occur due to incomplete oil impregnation leaving cavities in which discharges occur, high humidity in paper, arcing between bad connections, shielding rings, adjacent disks or conductors of windings, broken brazing. These result in heating in the range of 100 degrees to 700 degrees [7].
- Eddy current heating in magnetic core due to malfunction of the magnetic circuit. Large negative or zero sequence currents, or circulating currents in the tank and core lead to heating with temperatures rising above 700 degrees [7].
- Voltage surges with high rate of rise of current, short circuits in the secondary and rapidly fluctuating load currents.
- Explosion of the Diverter Switch connected to On Load Tap Changer due to accumulation of combustible gases
- Poor mechanical contacts at bushings leading to sparks, loose springs in the tap changing contacts, pitted contacts of tap changer, fire in vapor accumulating above the oil, bad maintenance practice and condition monitoring (Figure 3). Improper lug connections, and terminals tightened without locknuts, result in the connections becoming loose with time, and when high starting currents, for instance, of motors pass through the loose connections spark occur which may ionize the chamber resulting in explosions [6].

Figure 3: Bolt holes of the lug of the transformer destroyed by fire (www.lankaweb.com)

In Brazil, power grid blackouts are included as one of the major national disasters [8]. It has a demand of about 60 GW, and a generation installed capacity of 94 GW, mostly hydroelectric. The transformer capacity set to rapidly increase is about 200 GVA. A variety of problems leading to transformer fire are experienced including a 150 kVA autotransformer (one autotransformer for each phase) where the water spray system failed to work and oil leakage spread the fire. In another case the whole substation became unusable as the busbar structure collapsed (Figure 4). In a third case, the power station transformer fire wall did not function properly allowing the fire to spread to other step up transformer units. In another situation, the fire sprinkler is wrongly installed facing the bushing; when a false alarm set it working it sprayed the bushing with water resulting in an external arc resulting in an explosion. If the transformer is improperly located in a generator station, the fire or combustible material are drawn into the turbine inlet systems.

Figure 4: Overhead structure fire that cause metal structures to sag and collapse. (http://electrical-engineering-portal.com/arriving-at-the-scene-of-a-power-substation-fire)

Causes of transformer explosion (Figure 5) are [8-9]:

- Poor maintenance of oil, leading to gradual decay of insulation level due to moisture contents increasing, on line tap changing sparks, constant overload heating, and partial discharges [10-12]. Poor maintenance of Buchholz relay (on transformer or on diverter switch) which is the first line of protection from fire [7]. Tracking down which relay(s) tripped helps in the diagnosis of the problem.
- High leakage current due to heavy overload
- Turn to turn and layer to layer fault caused by insulation deterioration caused by the high leakage current.
- Now, resulting from layer to later fault, a high fault current trips the primary fuse.
- Reclosing or refusing large arc current caused by complete insulator break down
- Hydrogen and methane gases produced as the high energy arc gasifies the oil.
- Pressure builds up above the oil level leading to transformer tank or cover being blown out. The pressure relief devices are unable to handle suddenly increasing pressures.
- Fast flying metal pieces scrapping against other pieces and the arc ignites the gas causing explosion.

Figure 5: Transformer explosions (http://video.news.com.au/v/75639/)

Infiltration of water, core insulation degradation, presence of leakage currents and treeing, and malfunctioning tap changers are all potential origins of arcs that lead to fire [11-12]. Buildup of gases inside the transformer tank or bushing lead to rupture, failure and fire. Most transformer oils withstand heat up to 146 degrees to 300 degrees, above which the oil catches fire. Transformers that are rated above 100 GVA need to have an automatic water spray systems [8].

As mentioned above maintenance and condition monitoring, including of the transformer insulating oil, are crucial. The protective devices such as the following must be housed in environmentally protective enclosures: gas relay, oil and winding temperature sensors, pressure relief devices inside the tank and tap changer protection relay. Moisture, rain, sunlight and pollution all have an ill effect on these protection systems. Tap changers must be inspected regularly (once in six months or twelve months) for mechanical wear, low dielectric strength. Tap changers are one of the most frequent causes of transformer failures. Substation tap changing transformers experience more failures than generation tap changing transformers, since the substation tap changers are more frequently and automatically operated. Bushings, through which oil may spill out, must be well sealed to prevent contamination by oxygen (oxidization) and humidity (hydrolysis). Seals must be regularly inspected for corrosion or other degradation. All mechanical connections, including that of bolts, of capacitive tap must be properly made, since loose connections lead to sparks. Pollution accumulating on insulators must be inspected and washed. Long term horizontal position storage of bushings must be avoided. Good maintenance of the transformer ensures maximum efficiency of operation, minimize the risk of pre-mature failure and breakdown and ensure optimum life time.

3. PASSIVE PROTECTION

The aim of passive fire protection is to prevent or limit damage to adjacent equipment due to the electrical failure in transformer [13]. There are three construction features considered such as oil catchment areas, heat radiation barriers and oil drainage system. The oil catchment area is constructed to avoid discharged oil from flowing across non-absorbent ground surface (Figure 6). This area is provided around major transformers and auxiliary transformer where any oil discharged is confined within the catchment area and reduced the potential of burning oil from endangering the main transformer respectively. By connecting the auxiliary oil catchment area to the catchment area for the main transformer, a lower bund wall is needed. The bund wall is also used to separate the oil cooler bank and main transformer.

Figure 6: Transformer oil containment (http://www.transformer-oil-containment.com/)

The second feature is an oil drainage system which it leads to minimize the severity and duration of fire in the catchment area. The oil conveyance from the fire originated in the catchment area of adjacent equipment is prevented by using standard 300mm concrete piping and separate the oil drainage system from the storm water drainage. In this system, the off-terrace oil containment is provided at the termination point of drainage pipes which oil pollution of the environment is prevented. An open holding dam is one type of off-terrace oil containment where automatically displaced the storm water by oil. Heat radiation barriers are the third construction features of passive fire protection (Figure 7). This barrier is provided when the minimum separation distance of 23 meters between adjacent buildings and switchgear cannot be achieved. In addition, a minimum height of 0.5 meters above the transformer tank and at least to the width of the oil catchment area is constructed for the heat radiation barriers between the transformers. In order to avoid direct flame impingement, minimum clearance of 1.5 meters is allowed between the bund wall and the barrier. Fire protection system is impossible to be provided at every substation economically. Thus, some criteria are evaluated to determine either it should be provided or not. Then, two options are considered if the fire protection is provided at the substations which are passive or active fire protection. In telecommunication installation oil free transformers are used to reduce the risk of fires [14]. In these transformers epoxy resins are used as insulators. They are costly compared to oil-transformers, almost double in price. But they are estimated to have a five percent overall economic advantage given the smaller space occupied, lower power loss when used for digital systems, and easy maintenance.

Figure 7: Firewalls containing the transformer fire (http://electrical-engineering-portal.com/substation-fire-protection)

4. HEAT REDUCTION USING HIGH EFFICIENCY TRANSFORMERS

All electrical equipment cannot achieve 100% efficiency with the usual losses in the transformer are core and winding losses where these losses are largely contribute to electrical system losses [15-16]. The losses of the transformer are not only depending on the design of the transformer. The other factor that needs to be considered is the operation load of the transformer. There are two operation loads in transformer that also contribute to losses and efficiency drop in the transformer: no load transformer losses and load transformer losses. In the no load transformer losses, the losses are due to magnetize phenomena in the core of the transformer. The losses are the self-power consumed in order to keep up with magnetic field in the core. There are two losses in core: hysteresis and eddy current losses. Hysteresis loss is occurred when the alternating current or voltage change from positive to negative which cause the reversal of magnetic field. There are energy is consumed during magnetic field reversal. This energy consumption is called hysteresis loss. Eddy current loss is occurred when self-induced current at core of the transformer [16].

The second operation load of transformer is called load transformer which cause load transformer losses. This is usually associated with full load current through the transformer winding. There is resistance in the winding and the material of the winding is usually copper. The windings losses are due to the resistance in the copper which cause losses in power at primary and secondary windings. Winding loss is also known as copper loss. Copper loss is varied by the I^2 of the load. Thus, the increase of load decrease the efficiency of the transformer. Table 1 [15] has shown the efficiency of the transformer (500kVA) decrease as the load increase.

Table 1
Transformer Load and Efficiency [15]

Load (%)	*25*	*50*	*75*	*100*	*125*
Efficiency at unity PF	99.10	99.14	98.97	98.76	98.52
Efficiency at 0.8 PF	98.87	98.93	98.72	98.45	98.15

5. CONCLUSIONS

With a significant number of transformers failing in any given power grid, and the failure sometimes leading to the extreme consequence of fire and explosion, there is a need specifically train and inform engineers that are expert in transformer maintenance, monitoring, diagnostics and proactive action when disasters occur. The insights and guidelines from case studies and reports from several countries including the USA and Brazil is presented. In Asia and the Pacific there is a lack of expertise on power transformers so that for reliable pre-failure diagnostics and revision of maintenance practice, it is needful to seek assistance from other countries. The paper sought to highlight and describe the proper installation, monitoring and maintenance of electric power transformers to prevent fire and explosion by considering the details of transformer parts that need close attention (e.g. transformer oil, mechanical connections, tap changers) as well as issues related to passive protection and transformer efficiency.

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