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Analysis of implications of toxicity and pollution associated with mineral oil explosion in high voltage T & D substations

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Abstract;

Electricity for today's society works similarly to the blood in our bodies. Transmission and Distribution (T & D) of electricity are impossible without the High Voltage T & D substation that works the same as our heart. Just like blood pressure and blood fat have risen in our hearts due to our lifestyle, the electricity substations' pressure has risen day by day equivalently. This stress of thirsty energy consumption has put more pressure on the electrical T & D systems, but it is also accompanied by ambient temperature rise. The explosion of power transformers and electrolyte capacitors is one of the increasing pressures on the substation's equipment. This explosion has many opposing points of the environmental impact discussed in our article, including soil, air, and water pollution due to burning completely and incompletely cellulose paper, mineral oil burning, and broken pieces of ancillary equipment scattered around the substation. By

analyzing mineral and silicone oil components, the rate of toxicity, and the amount of preservative of the smoke in detail, we will show how pollution can influence water and soil resources.

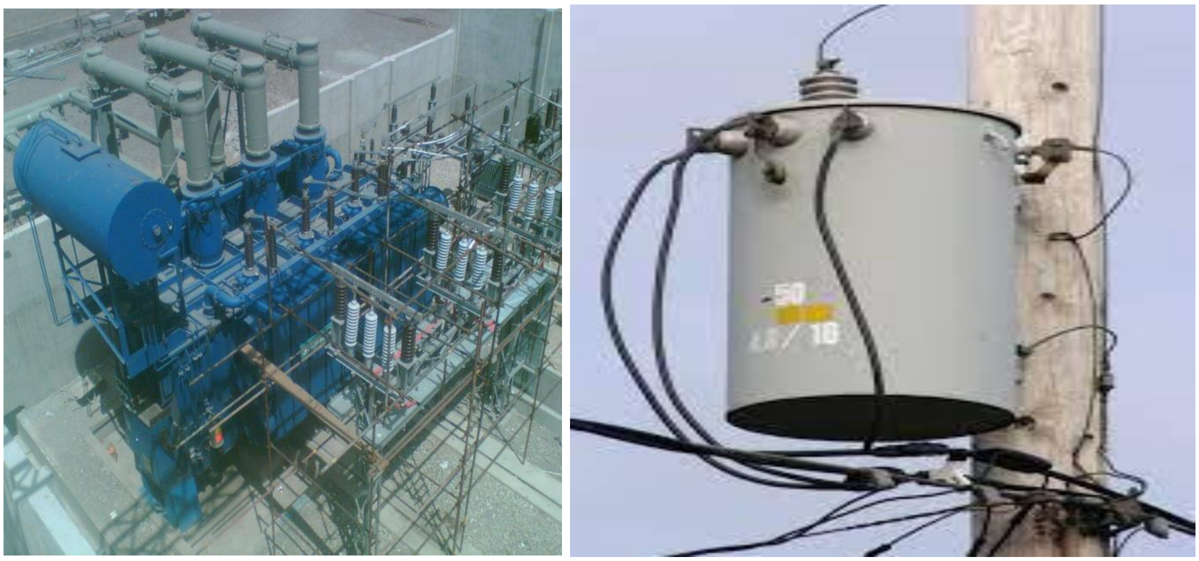
Introduction;

Transmission and Distribution (T & D) substations play vitally essential roles (Figure 1). There are a multitude of apparatuses to distribute, control, protect and measure the electricity in the T & D substations including disconnector switches, circuit breakers, capacitors, and reactors, busbars, insulators, cable, measuring transformers, Protection relays, automation system, grounding, etc. Some of the important functions include:

- Turning the current in the overhead or underground circuits ON and OFF, usually in an emergency.
- Making maintenance opportunities of equipment offline and hot-line
- Stepping up or stepping down the voltage level to transmit or distribute electricity
- Adjusting the stability of the electricity networks

Figure 1; A 420 kV Air Insulation Substation, Middle East, 2018

One of the primary devices making transferrable and usable electricity is the power transformer. It is used to increase voltage level from (e. g., 6-20 kV) to the higher voltage levels (e. g., 132- 800kV) to reduce nominal current and consequently reduce transmission's losses from generating power plants to the end-user location. Some step-down power transformers decrease voltage levels to supply energy at the appropriate safe voltage level residentially and commercially against step-up transformers. Two types of power transformers are shown in Figure 2; a) is a step-up and b) is a step-down transformer;



a) Step-up Transformer b) Step-down or distribution transformer.

Figure 2; A view of step-up and down transformers

The main internal parts of power transformers include active parts from winding, iron core, and accessories to mineral oil, insulation cellulose paper, and electrical and mechanical connection. The main external parts are bushings, mechanical and electrical protective devices, fans, radiators, and oil expansion conservators (illustrated in Figure 3). Since the power transformer is the most expensive and essential device in the T & D substation, many mechanical and electrical secondary protective devices are considered to keep the safe and secure regular operation of transformers. Engineers designed microprocessors and various types of sensors for online and offline control of the safety of power transformers. Technology development of the rate of power transformer capacity has increased such that the maximum power rate of the transformer was 380 MVA in 1970 while the enormous power transformer currently produced is more than 750 MVA [1] (enough to supply 13 percent of New York City alone) [2]. So, the importance of a power transformer in the electricity network stability is clear.

All components are immersed in mineral oil to have the best cooling and electrical insulation. Although there is little information about the amount of pollution footprint of the production of a power transformer, it is clear that there are a considerable number of pollutants in the manufacturing of transformers. The potential pollutant sources are linked to industries, including steelmaking plants, copper production, paper, and core steel. In this article, we will focus our discussion on pollution associated with the operation of power transformers only.

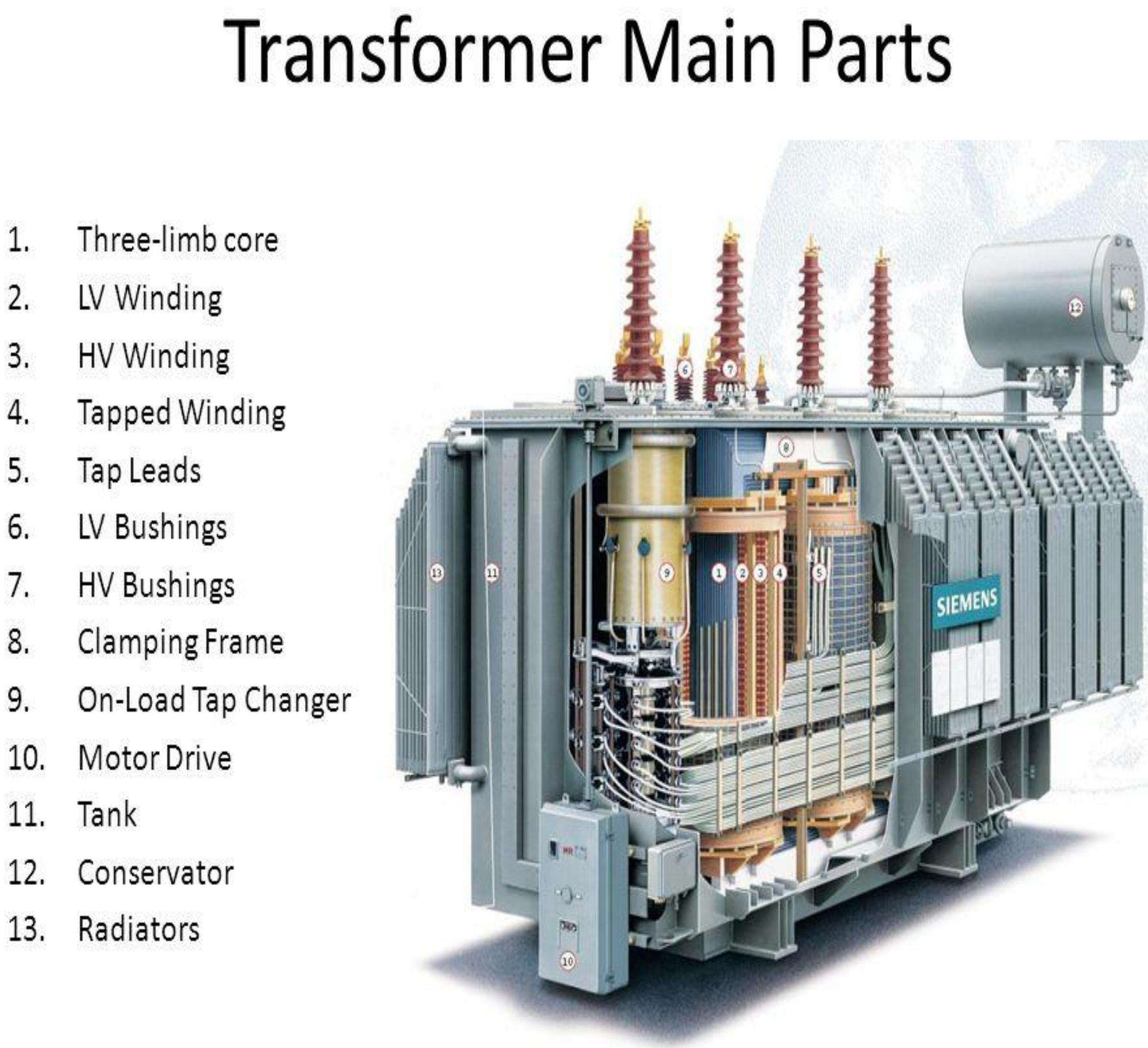


Figure 3; A section of main internal and external components of a power transformer,

https://slideplayer.com/slide/6944603/

Background;

These days many continuous monitoring devices are designed for online monitoring of all parameters related to transformer condition. Most of these parameters include nominal current, total harmonic distortion percentage, temperature maximum of the oil and winding, real-time temperature of winding and oil, the load percentage real-time, overloading, the ratio between oil analysis of emission including H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CO, CO_2, and total dissolved combustible gas (TDCG). The best way to control the ratio between these gasses is using dissolved gas analysis (DGA). The more electricity demanded, the more current passes, the more current, the more power losses and the more heat generated. Controlling the winding continuously as a source of heat and then checking the temperature of the oil is a critical parameter to avoid flashpoint and every hot spot making and breaking every insulation. Many unwanted situations frequently happen in the electrical grids such as unusual environmental circumstances, an outage in some parts of the network (including power plants or lines and substations). Changes in load voltage and harmonic pollutants are some of the emergency stresses on the electrical system in general and power transformers in particular.

These conditions, plus the aging factor of transformers, increase the risk of the transformer's operation due to probability and the intensity of risk factors. The failure rate varies considerably between transformer users. It depends on the design and manufacture quality, the procurement policy, and the operation and maintenance practices. Statistics confirm the failure rates increase on transformers with operating voltages above 300 kV, and the consequences of a failure fire are more severe on systems with high fault levels [3]. Table 1 shows the number of transformer explosions in the Canadian network from 1965 to 1985 over 20 years.

Canadian Utility Statistics for the Period of 1965 to 1985			
Voltage class (kV)	Number of explosions	Number of oil spills	Number of fires
735	15	9	8
315	3	2	1
230	2	1	1
161	2	0	0
120	5	3	3
Total	27	15	13

Table 1; The Canadian transformers explosion from 1965 to 1985 in the Ultra High Voltage level, https://www.tdworld.com/substations/article/20964130/risk-equals-probability-times-consequences

The worse case in the outage of a power transformer is an explosion and catch fire the transformers. While engineers and designers have tried to do their best to use simulation and consideration qualified parameters using the advanced software and computer aid application, the expectation of the quality of electricity is rising sharply due to very sensitive appliances to the voltage fluctuation. It did mean one power transformer outage in 2020 has a higher negative point than three transformers in 1985 because many secure and safe communities are connected to the power stability; in terms of explosion or burning of a transformer, many toxic pollutants are released into the environment, including air, water, and soil.

Methodology;

The average probability of a severe transformer fire is on the order of 0.06% to 0.1% per service year or one fire per 1,000 to 1,500 transformer service years. This means 2.4% to 4% of all transformers can be expected to cause a fire during 40-year service life in practice. While the probability of a transformer fire is relatively low, it is not a negligible risk and certainly too high to adopt a do-nothing approach for most transformer installations. Mineral oil is a temperature-sensitive material that has a tremendous electrical insulation specification. Because of high pressure due to high voltage electricity and inside main tank high temperature, if pressure relief valve as an ultimate device to prevent the explosion did not work the explosion and perhaps firing will happen. However, although these days owners of substations have tried to install deluge systems and hot oil drain systems, the risk of catching fire is high. In terms of fire hazard, these things are likely to happen;

- A long length of black smoke with a huge flame in the top of the main tank of transformer
- Dispersal of hot oil to the surrounding environment
- A lot of broken pieces of ceramic bushings and glasses
- A release of toxicity halogen gasses and smoke due to firing PVC cable sheath.
- Some fire-fighting trucks may not be able to get close to the exploded transformer due to boiling area temperature.
- Taking at the high-level risk of bi-side transformers

  In Figure 4, one medium rate power transformer with 27,000 liters of mineral oil caught fire;

Figure 4; A 69 kV oil power transformer caught fire,

https://www.tdworld.com/substations/article/20972327/fire-protection-in-substation-transformers.

Before going into detail about the toxicity of pollution of oil explosions, we will see the normal range of dissolved gas ratios in Table 2. This ratio comes from IEC standards that are continuously under analysis every two years and is based on Roger's ratio method. Also, Table 3 shows the fault gas generation rates for a transformer with a 50,000-liter mineral oil capacity;

$\frac{CH_4}{H_2}$	$\frac{C_2H_6}{CH_4}$	$\frac{C_2H_4}{C_2H_6}$	$\frac{C_2H_2}{C_2H_4}$	Suggested Diagnosis
>0.1 <1.0	<1.0	<1.0	<0.5	Normal
≤0.1	<1.0	<1.0	<0.5	Partial Discharge corona
≤0.1	<1.0	1.0	≥0.5 or ≥3.0 <3.0	Partial Discharge- corona with tracking
>0.1 <1.0	<1.0	≥3.0	≥3.0	Continuous discharge
>1.0 <1.0	<1.0	≥1.0 or ≥3.0 <3.0	≥0.5 or ≥3.0 <3.0	Arc - with power follow through
>1.0 <1.0	<1.0	<1.0	≥0.5 <3.0	Arc - no power follow through
≥1.0 or ≥3.0 <3.0	<1.0	<1.0	<0.5	Slight Overheating- to 150°c
≥1.0 or ≥3.0 <3.0	≥1.0	<1.0	<0.5	Overheating 150°-200°C
>0.1 <1.0	≥1.0	<1.0	<0.5	Overheating 200°-300°C
>0.1 <1.0	>1.0	≥1.0 <3.0	<0.5	General conductor overheating
≥1.0 <3.0	<1.0	≥1.0 <3.0	<0.5	Circulating currents in windings
≥1.0 <3.0	<1.0	≥3.0	<0.5	Circulating currents core and tank; overloaded joints

Table 2; Suggested diagnosis from a gas ratio -Rogers ratio method

	Normal	Serious
H_2	Less than 0.1 ppm/day	more than 2ppm/day
CH_4	0.05	6
C_2H_2	0.05	6
C_2H_4	0.05	6
C_2H_6	0.05	1
CO	2	10
CO_2	6	20

Table 3; Fault gas generation rates for transformer with more than 50,000-liter mineral oil, A guide to transformer oil analysis by I.A.R., Gray Transformer Chemistry Services

Based on some Researches [4] when a transformer caught fire, more than the emission of toxic gasses caused tragedy to the atmosphere, many aquatic resources were impacted by various organic pollutants. Although many power transformers have underground oil recovery tanks, use of the compressed air foam (CAF) can pollute the surrounding area and extend the pollution level during fire fighting activities. These pollutants impact wastewater treatment and will change physical treatment to chemical treatment that has more cost and takes more time. Furthermore, the surrounding soil. Whether fighting activities or maintenance preventing exercises make environmental pollutants due to oil leakage and dispersion. However, National Fire Protection Association (NFPA) 851 has a lot of great instructions to protect the surrounding from fire risk and fire impact; it should be noted that many other parameters affect the risk of transformer explosion.

A combination of copper and aluminum plus iron and cellulose can increase concentrations of toxic compounds at some locations. However, although not proven yet, likely, all energy consumed when the transformer was constructed will eventually release into the environment and three associated categories of pollutants would be emitted to the environment: production pollutants, maintaining pollutants, and explosion pollutants. All toxic compounds dissolved into the oil will be released into the environment and contribute to air pollution thereby posing a risk to the soil and water resources. In Table 4, the results of the faults inside of the main tank are given. Although no one was injured or killed due to breathing the contaminants of the transformer which exploded, it is clear that the environmental impacts and the gasses emitted to the atmosphere (and potential climate change effects) had negative health consequences. Many workers and firefighters reported that their feeling was not good after they were exposed to the smoke and flames of the transformer due to breathing toxic gasses (www.MSC.IR, safety report).

Fault	Key Gas	Results
Corona discharge	Hydrogen	Low energy discharges create methane and hydrogen and smaller quantities of ethylene and ethane.
Arcing	Acetylene	Large amounts of hydrogen or acetylene or minor quantities of ethylene and methane can be produced.
Overheated Cellulose	Carbon Monoxide	If cellulose is overheated, then it will produce carbon monoxide
Overheated Oil	Methane and Ethylene	Overheating oil will produce methane and ethylene (300 degrees F) or methane and hydrogen (1,112 degrees F). Traces of acetylene might create if the unit has electrical contacts or if the problem is severe.

Table 4; the most common issues that can occur when testing transformer oil,

https://www.electrical4u.com/transformer-insulating-oil-and-types-of-transformer-oil/

Conclusion;

In this report, we reviewed some analyses and research related to power transformer explosions and drew upon personal experience from the observed results of a transformer explosion. Toxic gasses were released directly into the environment and due to some metal oxides of copper and cellulose carbon emissions, the rate of toxicity changed. Due to many policies and regulations to decrease carbon emissions, it should be noted that some transformer design, manufacturing, and operation condition should be revised. This is more important than the statistics show since the rate of transformer explosion is increasing because of the age factor and less quality of maintenance and bad operation[5]. Substation designers have to consider the NFPA 850 for standards spaces between equipment instead of concerning the costs and economy. Closing drainage connections to the wastewater system is an essential change when the T & D substations are designed to avoid impacts on water resources due to the toxicity of chemical materials linked to oil leakage and transformer explosion. However, some new solutions to avoid using oil inside of transformers' tank can not be substituted of oil in very large capacities such as the power more than 100 MVA. For example, Resin cast, SF6 gas, and Vacuum are some insulation that harms the environment. Consequently, keep the quality of oil and keep the operational condition at the optimum range can reduce the risk of transformer explosion and emission toxicity smoke and material to the surrounding spaces. Also, a transformer monitoring management system can help owners to reduce firing transformers.

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