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Review

Review on Gassing Tendency of Different Insulating Fluids towards Transformer Applications

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Abstract: This paper reports the critical reviews on the gassing tendency of different insulating fluids along with the precautionary measures to be considered during their fault diagnosis in transformer insulation. The experimental techniques and procedures for identifying the gassing due to electrical and thermal stress along with the stray gassing phenomenon has been elucidated. The different interpretation schemes used for determining the faults in transformers results in unexpected errors when the historical data relating to mineral oil is used for the other alternative fluids. Mineral oil and natural ester show a positive gassing tendency compared to synthetic ester which exhibit a negative gassing tendency. The stray gases are mostly due to breakage of C-C bonds under normal operating temperature of transformer. Among the different hydrocarbons, hydrogen and ethylene are more predominantly formed under lower temperatures. The silicone oil and ester fluids are more stable even under localised hot spots simulated observing a lesser gassing compared to the mineral oil. The impact of additives along with the oxygen and water content in the insulating fluids can lead to the stray gas's causing confusion towards the identification of actual faults occurring in transformers. Furthermore, the regeneration of insulating fluids using different adsorbents reduces the gassing tendency depending on the number of cycles used for its reclamation.

Keywords: gassing; mineral oil; ester fluid; hydrogen; ethylene; stray gassing; thermal stress; electrical stress; regeneration

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1. Introduction

The power transformer is one of the most important parts of the transmission and distribution network, where the reliable electric supply depends on the proper functioning of its insulation system. The insulation can take the shape of a single form (solid, liquid, or gas) or a combination of forms (solid/liquid, solid/gas) and, as a result, it can be categorized into three types, such as dry, gas, and liquid immersed transformers. Dry type transformers are typically cast resin based with core and windings not located within the tank, requiring less area for its installation. The use of epoxy resin to encapsulate the transformer winding prevents the moisture infiltration and it belongs to the type of class F insulation, providing an increased fire safety with better insulation resistance towards higher temperature [1]. They are best suited for interior installations in the distribution network closer to load centres, where they can save cost on cable by improving voltage control. Epoxy cast transformers have the benefit of being able to tolerate greater basic impulse levels and short circuit stresses [2] with a less cost involved in the cable due to its interior installations in the distribution network closer to load centres. Although dry type transformers have a superior performance, overloading for a prolonged period of time might cause the winding insulation to fail completely. Furthermore, dry type transformers run noisier than liquid immersed transformers [3], resulting in an extra expense for sound attenuation materials.

Later, gas insulated transformers with sulphur hexafluoride as an insulation and cooling agent were developed. The gas's non-flammability decreases the enclosure structure, making it possible for the subterranean installation. Furthermore, in the event of a problem, the pressure rise involved with gas filled transformers is minimal [4], lowering the potential threat of plant failure. However, the electric arcing causes sulphur hexafluoride gas to decompose, posing an issue regarding its compatibility with materials and raising issues concerning the safety procedures involved with insulation engineers [5].

Insulating fluid serves as the major dielectric in liquid immersed power transformers, where the functioning of spacers and mechanical support for the winding layers are provided by pressboard/paper insulation manufactured using the chemical reactions on the kraft paper [6]. Depending on the degree of polymerization, the cellulose polymer is a crucial component of pressboard and paper, and it is connected to each other via glucose units. Additionally, the state of the pressboard/paper insulation affects the transformer's lifespan and, thus, in the early 1950s, researchers focused on improving the thermal performance of paper insulation. Later, a better thermal behaviour of insulating paper by delivering an extra 10 °C rise in temperature was developed by National Electrical Manufacturers Association (NEMA, Rosslyn, VI, USA), bringing the maximum temperature for liquid immersed transformers with thermally upgraded paper to around 65 °C [7]. Both the insulating liquid and the pressboard/paper insulation inside the transformer can deteriorate with time, and, hence, its dielectric properties should be monitored on a regular basis. The pressboard insulation in the transformer needs to be changed as a consequence of the ageing process, while the sludge formed as a result of insulating fluid degradation are usually recovered using different adsorbents [8]. When comparing the various transformers as discussed above, liquid immersed transformers are seen to be more efficient and safer with a longer lifespan.

There are different kinds of insulating fluids used for the application towards the power transformers. Askarels, made of polychlorinated biphenyl (PCBs), were utilized as a transformer insulating fluid in the early 1970s due to their non-flammability. They are biphenyl molecules wherein the hydrogen atom is substituted by chlorine atoms, and they were utilized in adhesives, insecticides, turbine lubricants, and power capacitors in addition to its transformer applications [9]. PCB disposal into the environment can produce water contamination, sedimentation, and attachment to the soil layer, which can last for years. Incineration is a typical waste disposal method that can result in the creation of poisonous compounds, such as polychlorinated dibenzofurans, posing a serious health risk, and, finally, the use of PCB was outlawed for its usage in transformers and other applications in 1979 [10]. Due to the negative effects of PCB as a dielectric fluid in transformers, researchers looked at adopting silicone fluid as an insulation medium. Silicone fluid is a type of synthetic liquid (polydimethylsiloxane) that has a high thermal stability and has proven to be effective in power transformers. The presence of a methyl group in its molecular structure affects its viscosity [11], and a gelatinous material was found to appear on the electrodes during the partial discharge phenomena concluding its polymerization reaction. This problem associated with silicone liquid restricted its usage well below the inception voltage [12], and must be considered during the initial design stage of transformer. Apart from PCBs and silicone liquid, mineral oils purified by hydrocarbons during the distillation of crude oil stock were used in transformers. Based on the type of crude oil utilized at the refinery, mineral oils are classed into two types: one is the paraffinic based oil and other is the naphthenic based oil. There is a higher possibility for the deposition of sludges due to the lower oxidation stability of paraffinic oils on the windings and cooling channel of the transformers, thus limiting its heat transmission process. However, naphthenic oil's lower viscosity improves cooling performance, and its strong oxidizing stability minimizes the formation of sludges extending the transformer lifetime [13]. The presence of corrosive sulphur in mineral oil (disulphide, mercaptans, and thiophenes) can induce the degradation of insulating material, which can result in severe transformer failures over a long period of time. The sulfur-based chemicals found in mineral oil are non-corrosive and can attract free radicals that produce peroxide during the oxidation process [14]. Furthermore, owing to the lower flash point of mineral oil and the probability of fire threats imposed in power transformers along with its lower biodegradability has now led the researchers to look at alternate dielectric fluids [15].

Before introducing new insulating fluids to transformers, the researchers should focus on the design changes based on its dielectric properties and assess its performance under different stresses (electrical, thermal, and chemical) with reactions of oxidation and hydrolysis occurring mostly while the transformer is in service [16,17]. According to the National Electrical Code (NFPA 70), the thermal class of ester fluids enables them as a feasible alternative for installation in heavily inhabited regions or commercial structures, such as malls and airports. The increased hygroscopic nature of ester fluid compared to mineral oil makes them react with atmospheric air and, therefore, special care must be taken when storing and handling it, making them appropriate for non-breathing transformers [18]. Given the rising need for ester fluids in power transformers with voltages more than 100 kV, extra design improvements should be made to ensure that ester fluids within the transformer function properly [19]. The ester fluids provide a higher fire safety, increased probability index and higher biodegradability make them a viable option for transformer insulation [20]. Considering the above advantages of ester fluid over other dielectric liquids, it can be operated for transmission lines higher than 400 kV taking into account the entire cost of transformer installation. Ester fluids are divided into synthetic and natural categories based on their source and applicability to transformer applications. Natural esters have a glycerol backbone with various fatty acid groups that might be saturated, mono unsaturated, or poly unsaturated, whereas synthetic esters belong to a family of polyol esters containing pentaerythritol tetra ester [21]. The proportion of saturated acids relative to unsaturated acids determines the stability of ester fluids against oxidation and viscosity [22]. The impact of adding two different insulating fluids (esters and mineral oil) was further researched where the optimal concentration of esters was limited to less than 20% considering the better dielectric properties [23,24]. Thus, the advancement of insulating fluids with superior thermal and dielectric characteristics is generally required to satisfy the growing demand for high voltage insulation systems [25].

The loading cycle of transformers can impose various stresses on both solid and liquid insulation, changing its dielectric characteristics and it is responsible for the higher localized electric field and temperature variations inside power transformers. Considering the impact of different stresses exhibited by the transformer insulation, the thermal stress is responsible for majority of the failures occurring to transformer [26]. According to the conclusions drawn by Oommen and Prevost [27], the lifespan of paper insulation reduces by 50% for an increase of 6% in the hotspot temperature. In order to understand the degradation mechanism occurring inside the transformers, continuous monitoring of both the liquid and solid insulation [28] should be the critical objectives of power utilities and asset management, thereby mitigating failure involved in the transformer at their early stages. Hadjadj et al. [29] used UV-Visible spectrometry and turbidity measurements to examine the decay products involved during the ageing of transformer oil. It was concluded that acidic compounds produced on the insulating fluid during the ageing phenomena had a higher association with dissolved decay products and turbidity. Talhi et al. [30] studied the effect of various stresses on the electrification of unaged and aged conditions towards mineral oil quantifying that free radicals present in the insulating fluid had an effect on its electrostatic charging tendency (ECT). Furthermore, the ECT of the insulating fluid was shown to have a direct relationship with various dielectric parameters (decay products, turbidity, and moisture content) when evaluated under different loads. There are numerous chemical and electrical diagnostic procedures utilized for transformer insulating materials and, among the many approaches, dissolved gas analysis (DGA) was effective in detecting incipient defects, arcing, and cellulosic polymer degradation [31]. It is hypothesized that the connection developed using dissolved gas analysis approach might provide a better monitoring of the transformer insulation allowing the maintenance engineers to take the required safeguard measures before any failure occurs inside the transformer.

Considering the above-mentioned literature on the liquid immersed transformers and the occurrence of different discharges during its operational lifetime, the current work focusses on the gassing tendency of insulation fluids as a condition monitoring towards power transformers. The major work discussed is on the standardization of methods used for gassing, impact of stressing on the gas formation of different insulating fluids, the stray gassing effect on DGA interpretation, the effect of additives, and the regeneration towards gassing.

2. Experimental Section

The effect of different stresses exhibited by the insulating fluids and its impact on dissolved gas formation needs to be understood based on various experimental investigations performed under laboratory conditions. This section reviews the procedural techniques adopted for the evaluation of gasses under different stresses and stray gassing interference involved during the analysis of DGA.

2.1. Gassing towards Electrical Stress and Ionization

The insulating fluid inside the power transformer is subjected to electrical stresses, such as transient overvoltage and lightning impulse voltages other than fundamental AC supply voltages [32,33]. Currently, with the introduction of high voltage direct current (HVDC), transmission lines and various renewable energy resources for distributed power generation [34,35], the dielectric liquid should be able to withstand DC voltages and harmonic AC voltages with different total harmonic distortions (THD). Such electrical stress on the transformer insulation can initiate partial discharges at a very low voltages, thereby leading to the complete failure in the power transformers. Thus, the experiments on the gassing of insulating fluid were performed in a laboratory environment to understand better on the dielectric changes in the fluid under electrical stress. Initially, the IEC 60628 standard [36] was used for the analysis of gases after subjection to electrical stress. It involved two methods where the first one measures the gassing tendency in a hydrogen ambience with its rate of evolution of gas monitored after a short interval of time (120 min), and the second technique represents the gassing of insulating liquids with the rate of change in its gas volume tested after a time duration of 18 h. The major difference between the two methods discussed in the IEC 60628 standard are the test voltage and time duration used for the electrical stressing on the insulating fluid. Additionally, ASTM D2300 was followed for the gassing tendency of insulating liquids towards electrical stress and ionization [37]. As per this standard, the insulating liquid is subjected to radial electrical stressing after being saturated with any of the gases, such as nitrogen, argon, carbon dioxide, hydrogen or air, unlike the IEC standard where only hydrogen gas is preferred. Before applying the test voltage of 10 kV, all the precautionary measures must be followed during the gas bubbling on the test cell such that level of insulating liquid on both sides of burette are maintained at the same level. Due to the applied stress, the gas region above the insulating liquid layer becomes ionized, causing an ionic bombardment at the insulating liquid–gas interface and the changes in the pressure measured with respect to time are used to quantify the evolving or absorbing of gas in volume per unit of time.

The electrical stress (E_x) exerted on the insulating fluid at a distance X from the inner electrode is given by:

$$E_x = \frac{1}{XK_1} \cdot \frac{V}{\frac{\ln\left(\frac{d_2}{d_1}\right)}{K_1} + \frac{\ln\left(\frac{d_3}{d_2}\right)}{K_2}} \tag{1}$$

where V is the applied high voltage (10 kV), K_1 and K_2 represents the dielectric constants of insulating fluid and glass cylinder, d_1 indicates the diameter of the inner electrode, d_2 and d_3 corresponds to inner and outer diameter of the glass cylinder. Additionally, the gassing tendency (G) in μL/min calculated based on the above technique is given by:

$$G = \frac{(B_{t_2} - B_{t_1})K}{T} \tag{2}$$

where B_{t_1} and B_{t_2} indicates the burette reading after a time interval of t_1 and t_2 respectively, K represents the burette constant (μL/mm), and T is the testing time period $(t_2 - t_1)$ used for computing the rate of change in the gassing of insulating fluid. Along with the above standards discussed on the gassing tendency towards electrical stresses, the ASTM D6180 standard [38] which is generally used for understanding the stability of insulating fluid can also be used for simulating the electrical stress using the discharge test cell [39]. This technique involves a copper electrode sealed in a glass with a specific distance maintained between the electrode and surface of the oil. The discharge cell is to be vacuumed before the experiment and then high voltage of 10 kV is applied for a duration of 5 h. During this process, the pressure inside the discharge cell increases which is used for determining the quantity of gas. Arakelian et al. [40] have postulated the gas volume (V_g) based on the discharge energy (W) as:

$$V_g = \left(\omega_{lq} B_g^{lq} + \omega_{pl} B_g^{pl}\right) W \tag{3}$$

where ω_{lq} and ω_{pl} are the energy accumulated in fractions due to chemical reactions in liquid and plasma phase whereas B_g^{lq} and B_g^{pl} are the gas formation factors in liquid and plasma phases, respectively. The arc discharges involve major reactions in liquid phase compared to partial discharges. The shortcomings of this technique are the requirement of prior knowledge on the energy distribution in the liquid phases of the insulating liquid where in case of arc discharges, the arc burning time is also considered.

2.2. Gassing towards Thermal Stress

Thermal stress is one of the most important aspects that might influence the reliability of insulating fluids and shorten the lifetime of transformers [41]. Additionally, there is a higher possibility for the generation of gases even during normal operation owing to overheating caused by excessive overloading of transformer insulation [26], which should not be confused with the gases generated during the actual faults occurring inside the transformers. In order to understand the gassing tendency of insulating fluids under thermal stressing, the standard [42] was developed where it does not involve any additional electrical insulating materials during the thermal stress conditions. Initially, this standard was framed for investigating the gassing tendency in mineral oil alone and now it has been extended for all the other insulating fluids used in transformers. The ASTM D7150 standard involves two experimental methods for performing the gassing characteristics considering the higher probability for the formation of hydrogen and hydrocarbon gases in insulating fluids at a very low temperature. Since there is distinct gassing pattern inferred mostly after 164 h, the first method involves the investigation of gassing tendency at 120 °C for 164 h under both air and nitrogen ambience. Apart from the thermally stressed oils, the insulating fluids containing particular forms of contaminants may emit certain gases at lower temperatures compared to its actual conditions, thereby misleading towards the condition monitoring of power transformers. Thus, the second method involves the passing of insulating fluid through Fuller's Earth column with a specific ratio and flow rate to extract the organic impurities from affecting the gassing behaviour of the insulating fluids.

2.3. Stray Gassing

Stray gassing refers to the phenomena of fault gas production from insulating fluids at normal temperatures, caused entirely by their elemental constituents present in the liquid, and it is independent of the failure involved in the electrical equipment. It is not a unique phenomenon, but, compared to vegetable-based fluids, it appears to be closely related with the mineral oils. The generation of gases involving mainly hydrogen (H_2), methane (CH_4), and ethane (C_2H_6) from insulating mineral oils subjected to relatively low temperatures (90–200 °C) is known as thermal stray gassing. It has been inferred that, even when the transformers are not energized, predominance of such stray gassing activity (53%) has been noticed [43], and test results of DGA on transformers with this phenomenon resulted in a significant error. The inconsistencies associated with lower concentrations of hydrogen along with the presence of stray gassing raises further concerns on utilizing hydrogen and carbon dioxide as a suitable indicator towards the diagnosis of transformer faults [44]. Thus, it is worth noting that this thermal stray gassing should not be confused with oil gassing caused by gas-phase electrical discharges. Since 1998, several researchers have observed an unusual gas production at these reduced temperatures [45], and the findings of laboratory tests, on the other hand, were impossible to evaluate since they were collected under different test situations. As a result, a joint task force [46] was working on the objective to design a common testing method for the identification of stray gassing and interpretation towards DGA. Recently, this thermal stray gassing phenomena has been taken into account by various interpretation tools and standards associated with DGA, allowing a better discrimination between permissible stray gassing and unusual gassing produced by internal faults within the transformer. There are two different test procedures used to interpret the stray gassing of insulating fluid. The first one is the glass syringe technique where the degassed oil is saturated through either air or nitrogen gas, then placed at 120 °C inside an oven. The initial stray gassing phenomena is analysed after 16 h followed by sampling considered after 164 h to check any gassing limit. Later the sample is degassed and re-saturated with air or nitrogen to verify if there are remnant stray gases, even after the heat treatment process. The second technique involves heating the sample at 200 °C with three different glass vessels for the same ageing intervals as that involved with the first method to investigate whether stray gassing might affect DGA analysis at temperatures similar to those of problematic hot spots observed for the oil/paper insulation inside the transformers.

2.4. Test Methods and Interpretation Used for Dissolved Gas Analysis

There are different methods used for dissolved gas analysis. One of the common techniques used for analysis of gases in the electrical insulating liquid is through Gas Chromatography method, where the ASTM D3612 standard [47] indicates the precautionary measures that are to be taken care by the insulation engineers before performing the experiments. The chromatography-based technique contains three methods for extracting and measuring gases dissolved in electrical insulating oil with a viscosity of less than 20 cSt. To perform this measurement, the engineers normally do prefer a portable DGA kit from Kelman Transport X [48] where the equipment could be taken to the onsite condition for collecting the insulating liquid from power transformers providing reports on different dissolved gases and moisture content. Additionally, the interpretation of dissolved gases towards particular faults occurring inside the transformer can be determined using IEC 60599 standard [49]. This standard illustrates the mechanism of gas formation, identification of faulty conditions occurred within transformers based on the gas ratio and the recommended practice of representing the DGA results. Additionally, it is to be noticed that this standard is valid only for mineral oil filled transformers, and to extend this technique to other insulating liquids, it should be approached with a special caution. Further on, to overcome these limitations, the different insulating liquids, such as silicone oil, mineral oil, and ester fluids, used for transformers were provided with a separate interpretation guide [50–52] to take care of the analysis of dissolve gases. In general, dissolved gases are available at certain levels in the transformer oil [51], and the amount of gas produced is determined based on the type of faults. The major gases used for fault identification are methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2). These gases can give an indication of thermal faults occurring on the liquid/solid insulation, partial discharges, and arcing [16]. Several interpretation methods are used for the representing key gases responsible for faults occurring inside transformers and among them, IEC methods, Roger's technique, Key gas, and Duval's triangle are mostly preferred [53]. The different ratio techniques used for DGA can result in a range outside its expected limit and is thus recommended for its use along with key gas methods. Additionally, Duval's pentagon method was developed as an extension to the existing Duval's triangle which only considers concentration three gases towards fault prediction. Even though DGA procedures are extensively employed, several modifications are still required for effective diagnosis towards faults occurring in transformers. Additionally, the existing approaches are based on the trial-and-error methods, hence, an intellectual technique [54–57] is now formulated to reduce the inconsistencies involved in the interpretation of DGA results.

3. Discussion

3.1. Mechanism of Gas Evolution for Different Insulating Fluids

The insulating system of power transformers deteriorate under the influence of various stress during its operation, resulting in the formation of dissolved gases in oil. The detection of these gases can be extremely beneficial in diagnosing transformer faults and avoiding unplanned outages. The breakdown of hydrocarbon molecules in the insulating fluids owing to electrical and thermal stresses is the main reason behind the formation of gases [57]. The gases can either evolve or absorb depending on the fluid where the DGA is considered as the most informative approach for detecting and identifying the produced gases. The insulating fluids with negative gassing tendency (gas adsorption) are preferred by some of the utilities, although positive gassing tendency are acceptable when cost and supply are considered. There is no general consensus on the optimum ideal range of gassing values [58] and gas adsorbing oil may become gas evolving during the service lifetime. This indicates that early detection of aromatic concentration levels in the new oil and their preliminary glass inclination value can have a significant impact on gas formation over a longer period of time.

3.1.1. Gassing Tendency in Mineral Oil

Mineral insulating oil involves a combination of hydrocarbon molecules with different functional groups (CH, CH_2 and CH_3) which are either paraffinic or aromatic in nature. During the operation of power transformers, the degradation in mineral oil can lead to the formation of gaseous molecules as a consequence of multiple reactions, such as primary decomposition, free radicals, and other secondary chemical reactions [59]. When only a single hydrogen atom remains in a tiny fraction of a degraded hydrocarbon, it can react with the secondary atom to from a hydrogen molecule (H_2) as shown in Equation (4):

$$H\cdot + \cdot H \rightarrow H_2 \tag{4}$$

Furthermore, there is a possibility of breakage in the covalent bonds present between the carbon atoms of aromatic structure, where the atomic hydrogen reacts with the free radicals of methyl group [60]. In case of free breathing transformers, there could be various oxidation reactions upon the hydrogen and methyl free radicals generating carbon monoxide and carbon dioxides, as shown in Equations (5) and (6):

$$H_3C\cdot + \cdot H \rightarrow CH_4 \tag{5}$$

$$H_3C\cdot + \cdot CH_3 \rightarrow C_2H_6 \tag{6}$$

There are gases which gets formed only at higher temperatures (CH_4, C_2H_6, C_2H_2 and C_2H_4) with few gas (H_2) having the probability of generation at lower temperatures. The insulating paper/pressboard material, which are basically cellulose in structure connected through glucose molecules with the chain length determining its mechanical strength. These cellulose molecules contain different groups (CO, CH_2 and CH) among which C-O bond is weaker that can result in gases at lower temperature of less than 100 °C, and at higher temperatures, the insulating paper can result in the formation of CO_2 [61]. Other than the aforementioned gases, O_2 and H_2 are also present in transformer oil and are unaffected by electrical failures. The quantity of oxygen in the oil determines the level of CO and CO_2 gases produced, but the contradiction to the decrease in the O_2 content in oil frequently results in an abnormal rise in the operating temperature of transformer. As a result, the concentration of different gases may be linked to a certain failure mode or electrical faults inside the transformer with the volume of gas generation indicating the severity of defects [62].

3.1.2. Gassing Tendency in Silicone Oil and Ester Fluids

A practical test guide for gas analysis of silicone oil and natural ester filled transformers has been prepared by an IEEE working group comprising of various researchers from the test laboratories. Based on a large number of examinations on functioning transformers and laboratory research utilizing silicone fluid in insulation systems, a guide for interpretation is adapted similar to mineral oil. The main gases that have developed in silicone transformers are comparable to those that have evolved in mineral oil filled transformers. However, the volume and ratios of gases created vary depending on the circumstances with a substantially larger quantities of carbon oxides seen in typical silicone transformers can be considered as a noticeable distinction. Although the various insulating fluids and changes in the design of transformers can exhibit different results in its gassing tendency, the threshold levels have been formulated by IEEE research groups based on historical data from both distribution and power transformers [63]. The total dissolved combustible gases (TDCG) involve the addition of all the gases and there are different criterions [64] established with recommended action towards the normal operation and its extreme faulty conditions in power transformers.

Wang et al. [65] has studied the effect of partial discharges (PD) and sparking faults on the gassing of mineral oil (Gemini X) and natural ester fluid (FR3). According to their observations, both the mineral oil and natural ester results in hydrogen and acetylene as a major gas during PD and sparking faults, concluding that same gas techniques can be used for both insulating fluids. Despite the overall amount of fault gases in natural ester to be higher than mineral oil under PD fault conditions, the TDCG was identical in both cases with an increased gas formation in FR3 at the occurrence of PD. The ASTM D2140 standard used for calculating the carbon composition involved in insulating liquids was performed and a negative gassing tendency is exhibited for the naphthenic oils with increased aromatic content [66]. Although the natural ester fluid does not contain aromatics in its chemical composition, it contains a sufficient number of polyolefins which is responsible for its negative gassing tendency. Compared to the natural ester, the synthetic aromatic has a higher negative value of gassing, hence, it is easier for its blending with the mineral oil. Thus, the natural esters are mostly gas absorbing in nature with the synthetic ester showing the gas evolving characteristics. The natural esters are preferrable only for sealed transformer units [18], and even if the gas ratio caused by electrical faults in mineral oil and natural esters are same, the interpretation of faults in natural esters and synthetic esters would show a different value as compared to mineral oil [67]. However, considering the different techniques available for the interpretation of faults in transformers, the Duval triangle method [18] used for mineral oil can used to a certain extent for natural ester filled transformers without any modifications.

When exposed to localised hot spot stressing, silicone oil and ester fluids proved to be significantly more robust than conventional mineral oils. The presence of ageing inhibitor is one of the most important factors which along with higher flash point of ester fluids is responsible for its higher stability under localised thermal stresses compared to mineral oil [24]. In practical conditions, the gas ratios of alternative fluids are not identical to mineral oil when it comes to identification of defects and fault diagnosis. Hence, with the less data available on the gassing of synthetic and natural ester from laboratory conditions, there is little clarity on the permissible gassing levels allowed for such alternative liquids in the real time power transformer operation.

3.1.3. Gassing Tendency in Mixed Insulating Fluid

The mixed insulating fluids are also gaining more importance where the different percentages of ester fluid are evaluated with mineral oil, and it is inferred that 20% ester fluid addition to mineral oil gives a better performance in its dielectric properties along with the reduction in its gassing tendency [68]. When 20% of ester fluid was added to the mineral oil for its investigation on gassing tendency by performing heating at 600 °C for a duration of 3 min, the gas evolution was almost five times lower than its measurement performed separately towards mineral oil and ester fluid. Compared to mineral oil and ester fluids, the optimum addition of ester fluids to mineral oil can reduce the gassing involved during the thermal stresses. Although the mixed insulating fluid shows a better performance towards localised thermal stress, the impact of different stress (thermal, electrical, and chemical) towards its gassing tendency over a longer operational time is to be understood clearly before its application towards real time power transformers.

3.1.4. Impact of Additives on Gassing Tendency

The insulating fluid have long been investigated with various additives for its specific dielectric and physico-chemical properties towards transformer applications. The additives can serve the purpose of inhibitor, suppression in pour point, scavenging of free radicals, and passivation [69,70] on the insulating fluids. As per ASTM D3487 [71], 2,6-ditertiary-butyl paracresol (DBPC) and 2,6-ditertiary-butyl phenol (DBP) are accepted for their addition to a specific weight percentage on mineral oil towards transformer applications. Additionally, the addition of additives, such as DBPC and Benzotriazole [72], have shown a better performance reducing the electrostatic charging tendency of insulating fluids. There have been various reports on the failure experienced in power transformers due to copper sulphide formation on the winding and paper/pressboard insulation [14,73]. Hence, in order to mitigate the hazards due to copper sulphide, Igramet 39 with a concentration of 100 ppm [74] has been found to provide a surface coating on the copper layer thereby preventing them from catalytic reaction of sulphur species. Compared to mineral oil, the ester fluids contain inherent antioxidant additives, such as tocopherol [75], or it can be added externally with other additives, such as citric acid, propyl gallate, and ascorbic acid [76], to improve the dielectric performance. It has also been concluded that combination of different additives can result in better performance for transformer applications. Although the impact of additives has improved the dielectrics characteristics of insulating fluids, its influence on the gassing tendency should also be considered. The first report on additives towards gassing tendency was given by Clarke and Reynolds [77], where an increased concentration of additives caused simultaneous reduction in the gassing of mineral oil with higher electric field strength. The aromaticity of the insulating fluid has also been correlated with the gassing tendency revealing an increased gas adsorption with increased double bond concentration levels [78]. Later studies on the additive towards transformer oil have concluded that Butyl Hydroxy Toluene (BHT) and DBP [79] observing a negative correlation on the field strength with no change in the gassing tendency. The reason for the above variation in the additives was due to its aromatic hindered phenolic structure compared to the earlier literature, where it was aromatic in nature with a degassing tendency. Similar behaviour of increased breakdown strength in natural ester was noticed with citric acid and propyl gallate [80] relating to gas adsorption characteristics.

3.1.5. Impact of Stray Gassing on Dissolved Gas Analysis

There have been a large number of stray gassings on the insulating fluid over many years, where many researchers indicate that introduction of alternate types of insulating fluids along with hydrogen generation at lower temperatures are responsible for this phenomenon [81]. The passivation of insulating oil which is used generally for preventing the copper corrosion in both winding/pressboard insulation can also increase the formation of stray gassing [82]. The stray gassing can occur due to various chemical reactions happening inside the power transformers at normal operating temperature conditions, thus, it makes it difficult for the insulation engineers to identify the actual faults that have been generated. The molecular structure of insulating fluids is an important factor where Tomita and Ito [83] have studied the different carbon types involved in various derivatives of mineral oil (paraffinic, naphthenic, and aromatic) towards stray gassing using Gaussian process. It has been inferred that DGA and GC/MS analysis could not detect this stray gassing, whereas the Gaussian technique detected the breakage of C-C bonds generating low molecular weight gases responsible for stray gassing. The studies on stray gassing of synthetic ester with pentaerythritol base indicated a higher amount of ethylene with natural ester showing increased concentrations of hydrogen and ethane, respectively [84]. Furthermore, the factors, such as heating temperature, time, oxygen concentration, and the addition of copper and additives [85,86], were tested on mineral oil concluding that irrespective of insulating oils, all the above parameters could accelerate the formation of stray gassing. Daniel Martin et al. [87] have not only considered the effect of stray gassing experiments at varying temperature, but also investigated the impact of different oxygen concentration and water content towards the gassing on transformer oil. Based on the above experimental conditions, the authors conclude that water content on the insulating fluid can release hydrocarbon gases with ethylene at a higher concentration level. Hohlein [88] studied the different unusual cases occurring in a transformer during its service indicating the generation of hydrogen and ethylene mostly during the stray gassing phenomenon. Additionally, it was indicated that hydrogen gas production depends on the temperature and is observed in hydro-treated oils. In order to isolate the stray gases from PD and thermal faults, Duval [89] has proposed different techniques to identify stray gassing in mineral oil and alternative fluids used for transformer applications. Although stray gassing does not cause any threat to the transformers, it is not desirable since it may conflict with standard DGA interpretation systems. Thus, it is preferrable to use inhibited oils with a higher oxidation stability to reduce the evolution of stray gases. A summary of the gassing tendency of different insulating fluids is shown in Table 1.

Table 1. Characterization on the gassing of different insulating fluids.

Methods Used for Gassing	Mineral Oil	Natural Ester	Synthetic Ester
IEC 60628 (μL/min) [66]	21	−80	25
Gas volume (ml) due to localised heating [26]	15	2	6
Stray gassing (H_2 and C_2H_6) (ppm) [67]	10, 5	970, 550	85, 96
TDCG (ppm) due to arcing and hotspot	1100, 2000	1500, 1700	4950, 4000
Duval triangle for electrical fault [18]	-	Fault zones in mineral oil could be used	Fault zones in mineral oil could be used
Duval triangle for thermal fault [18]	-	T1 zone in mineral oil should be modified	T1 zone in mineral oil should be modified

3.2. Effect of Regeneration towards Dissolved Gas Analysis

The deterioration of insulating fluid begins during the energization phase where it is exposed to multiple stresses resulting in a sequence of chemical reactions. As a result, the acidic and polar substances dissolve in the insulating fluids, forming sludges which, in turn, affects the heat transmission process between the transformer windings [90]. Thus, the regeneration of insulating fluid should be performed to avoid the aged fluids from degrading the active sections of the transformer. Regeneration improves the dielectric characteristics of insulating fluid by adsorbing the acidic compounds and solid contaminants formed as a consequence of ageing during the transformer service lifetime. Additionally, the reclamation procedure eliminates not only the contaminants formed by the aged fluid, but also removes the inherent natural chemicals present in the insulating fluid, making them not suitable for use inside the transformers [91]. Mostly this reclamation process is advisable only for the transformers, reactors, and circuit breakers, and not suggested for capacitors, cables, and generators. Different procedures are used for the refinement of insulating fluid according to IEEE C57.637 standard [92], and descriptions of methods include diverse materials, contact approaches, and infiltration mechanisms. Additionally, with continuous repetition in the treatment process, the impact of reclamation decreases, adding sulphur compounds to get dissolved into the fluid [93], which should be considered before re-using those fluids as a dielectric medium inside transformers. There are different adsorbents (Fuller's Earth, bentonite, and activated charcoal) used for the reclamation process towards insulating fluids [94,95]. Saffidine et al. [8] investigated the transformer oil that was aged for 38 years and optimized the quantity of multiple adsorbents required for enhancing the permittivity and resistivity of insulating fluids after the reclamation. Similarly, a membrane separation technique was used for purification [96] of insulating fluid and a reduction of 83% and 50% was noticed in its dielectric properties such as acidity and resistivity. Additionally, it is inferred that reclamation of insulating fluids with different cycles using Fuller's Earth [39] can reduce the gassing tendency, confirming that dissolved gas results get affected by decay products involved during the ageing phenomenon. Furthermore, it is concluded that gassing of liquids depends both on the chemical constituents of the hydrocarbon and with its purity [97]. Thus, considering the advantages of reduction in the gassing tendency of insulating fluids with regeneration, the insulation engineers should also check for corrosive sulphur content and percentage of natural antioxidants present after the reclamation, then re-utilize them for transformer applications.

4. Conclusions and Future Scope

A complete overview made on the gassing tendency of insulating fluids are as follows:

- The identification of gases formed in different insulating fluids under electrical and thermal stresses should be performed as per the standards postulated with separate interpretation guide established for mineral oil and alternative fluids for transformer applications. To identify and isolate the stray gassing from coinciding with the actual faults occurring inside the transformers, the experiments should be performed under lower temperatures of around 90–200 °C. Additionally, among the different interpretation schemes used for the identification of faults, the Duval pentagon method is the most prominent technique that considers the concentration of all gases compared to Duval triangle method which considers only three prominent gases (CH_4, C_2H_2 and C_2H_4).
- The hydrogen atoms formed due to primary decomposition in the insulating fluids is responsible for the formation of other hydrocarbons. Additionally, the quantity of oxygen level in transformer can accelerate the degradation of insulating paper resulting in carbon monoxide at lower temperatures and carbon dioxide at higher temperatures.
- Based on the aromatic content present in the insulating fluid, the gases formed can either get absorbed or evolved. Due to this characteristics, mineral oil containing aromatic hydrocarbons and natural ester containing polyolefins in their chemical composition results in positive gassing tendency compared to synthetic ester which shows the negative gassing tendency.
- The aromaticity of insulating fluids can be related to the gassing tendency whereas the additives, such as BHT and DBP, which are aromatic hindered phenolic structure shows a negative correlation with field strength. This phenomenon holds good not only for mineral oil, but also for the alternative fluids used for transformer operation.
- The stray gassing phenomenon can be formed due to the usage of non-inhibited oils, addition of passivators, oxygen concentration levels, and water content in the

insulating fluids. In addition, the reclamation of aged insulating fluids can reduce the gassing tendency, but a special care must be taken by the insulating engineers on the sulphur content that is getting exchanged during the process and the level of antioxidants before reusing them inside the transformers.

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