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On Some Imperative IEEE Standards for Usage of Natural Ester Liquids in Transformers

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ABSTRACT From the recent past, biodegradable dielectric fluids are becoming popular across the global utilities for use in oil-filled transformers. To date, several utilities have started using biodegradable insulating fluids for new and retro-filled power and distribution transformers. The intent of this article is to compare and analyze various aspects that are involved in the successful operation and maintenance of mineral oil and ester filled transformers. The comparative analysis in this article is aimed at properties, condition monitoring, diagnostic, and reclamation aspects of ester filled transformers. The imperative and pertinent standards, including IEEE Std C57.106, IEEE Std C57.104, IEEE Std 637, IEEE Std C57.147, and IEEE Std C57.155 remain the target objectives for potential analysis. It is hoped that this critical analysis will be useful for utility and condition monitoring engineers in understanding several key aspects of ester fluids vis-à-vis traditional insulating fluids. The present analysis might also be useful for researchers and industry interested in alternative dielectric fluids for transformer insulation technology.

INDEX TERMS Ester liquids, insulating oils, transformers.

I. INTRODUCTION

Transformers play an essential role in maintaining the voltage levels and reliability of power supply in transmission and distribution networks. The failure of a transformer in the electrical power network is generally accompanied by huge financial and technical damage to the utilities. Thus, demanding the need for efficient and accurate condition monitoring activities. In oil-filled transformers, most of the failures are confined to the integral parts of the insulation system [1]. Insulating liquid characteristics influence and govern the performance of the insulation system in oil-filled transformers. Over the years, various insulating liquids have been come to existence due to various reasons and requirements. However, mineral oils have been the most successful candidates across the global [2]. The standards practice for maintenance, condition monitoring, and reclamation of mineral oils have been drafted in [3]–[5].

Nevertheless, due to biodegradability, high thermal limits, health and safety requirements, sustainability, and demand for high performance insulating liquids, ester liquids have become popular in recent decades [6]. Majority of the global research is affirmative towards the use of these alternative dielectric liquids and is established that the performance of new liquids is comparable to mineral oils. It is to be mentioned that, the viscosity profile and resistance to lightening impulse in ester liquids is inferior as compared to the mineral oils [6], [7].

Several utilities across the globe have started using ester liquids for new transformers, while a few have been retro filled the existing units. The majority of these have been started using them as a representative sample to understand the integral characteristics and service behavior of the new liquids. However, most of the utilities challenge the lack of proper design guidelines, condition-monitoring tools, knowledge on end-of-life behavior, and diagnostic limits. The cost of the new insulating liquids is also one of the major issues; however, the cost of the dielectric liquid may be evaluated in several aspects. If liquid to liquid is gaged directly, the cost of ester fluids is higher than that of the mineral oil. To date, research on ester liquids out posted the technical benefits of using the new oil. The increased fire safety margin and ecological, health, and safety aspects far outweigh the increased cost. It is to be recalled that

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transformer insulation systems are designed to last for several decades in-service, and hence limited information on retro filling and mixed dielectric fluids is another challenge to be considered.

The IEEE standards association has reported the dedicated standards for the acceptance and maintenance of ester liquids [8] and dissolved gas analysis (DGA) [9] in ester-filled transformers. This allowed utilities and engineers to have separate standards for mineral oils and non-mineral oils. The condition monitoring aspects and diagnostic tests (characterizations) have been a focus of the existing standards, while diagnostic limits and regeneration aspects of ester liquids have been least emphasized. Hence, the existing non-mineral oil standards still require several improvements and much expanded knowledge on the new dielectric liquids. The same has been the present focus of various working groups, task force teams, and technical committees involved with the development and establishment of knowledge on ester liquids. Thus, considering the contemporary scenario in acceptance of the ester liquids with global utilities and researchers, there is a need to understand the existing standards from a much wider perspective. Therefore, authors have emphasized on the critical analysis of the following important IEEE standards: i) Mineral oils: IEEE Std C57.106 (acceptance and maintenance), IEEE Std C57.104 (Dissolved gas analysis), and IEEE Std 637 (reclamation). ii). Ester Liquids: IEEE Std C57.147 (acceptance and maintenance), IEEE Std C57.155 (Dissolved gas analysis). As the present manuscript is mainly focused on, the said IEEE standards, all the evaluation methods and limits discussed in this analysis are obtained from the same standards [3], [5], [8] for analysis. Henceforth, to avoid duplication of the large number of evaluation titles, the citation of the titles is avoided. However, the details of the same are available in [3], [5], [8] for readers. It is to be mentioned that, in order to emphasize, critical hypothesis concerning behavioral differences, similarities, and critical observations on both liquids, pertinent and related citations from the available literature are included.

The considered standards and guides are analyzed in a way to understand the similarities and differences among the standards for mineral oils and non-mineral oils. The sections of this article are organized in a way that utilities engineers and researchers may understand the critical differences between the properties and condition monitoring aspects of mineral and ester liquids. This will allow propelling the research progress to attain further developments most appropriately. This analysis will also be helpful for the industry in understanding the key condition monitoring aspects of the new ester filled and retro filled units

II. DIELECTRIC LIQUIDS ACCEPTANCE AND EVALUATION

A. EVALUATION METHODS AND PROPERTIES

Insulating liquid properties are the characteristic attributes through with the serviceability and effectiveness of the liquid are accessed to ensure the potential functionality of liquid insulation. Insulating properties include electrical and physicochemical properties, which are evaluated using different standard test methods. The details of which are discussed in IEEE Std C57.106 and IEEE Std C57.147 for acceptance and maintenance of mineral oils and ester liquids, respectively. The purpose of IEEE Std C57.106 includes evaluation procedures for acceptance of new (unused) mineral oils received from manufacturer separately and new oils filled in apparatus. The evaluation procedures for in-service mineral oils and serviceable conditions, along with storage and handling procedures, have also been discussed. It is to be mention that reclamation procedures and evaluation of reclaimed mineral oils have partially addressed in IEEE Std C57.106. Also, they are drafted in IEEE Std 637 in more detail. Similarly, the purpose of IEEE Std C57.147 dealt with evaluation procedures for the acceptance of new natural ester liquid for new and retro fill applications. The details of handling and evaluating the new liquid for on-site and storage activities with maintenance procedures have been outlined. IEEE Std C57.147 also covers the reconditioning, reclamation, and environmental procedures for natural ester liquids. However, the discussion of reclamation, retro filling, and miscibility aspects are presented in a later section. In this section, the evaluation test methods, properties, acceptable limits, diagnostic limits (where available) of both the liquids (mineral oil vis-à-vis natural ester) are summarized.

The basic properties of insulating oil and various characteristics are listed in ASTM D117. However, all the significant properties have been addressed in both IEEE Std C57.106 and IEEE Std C57.147. The evaluation methods of mineral oils and natural ester insulation liquid are slightly different as per the said standards. This difference is because of the inherent changes in the chemical composition of both the liquids. However, most of the evaluation methods remain the same for both the liquids, while a few are slightly updated. Even though the significance and scope of the characteristic properties remain the same, there is a need to understand them separately with the appropriate evaluation methods. Given differences in the chemical compositions, the intensity of aging reactions and nature of the aging byproducts varies. To better understand and ease the analysis, various properties discussed in IEEE Std C57.106 and IEEE Std C57.147 are sub characterized as electrical and physical and chemical properties in this section. It is to be mentioned that all these parameters are highly interrelated. A careful understanding of different parameters is essential to understand the insulating liquid's performance and ensure proper maintenance of the in-service units.

1) ELECTRICAL PROPERTIES

Electrical properties are the most important characteristics that a potential insulating liquid is to be evaluated for minimum satisfactory performance. However, this satisfaction level is to be within the agreement of the manufacturer and the customer. Both ASTM D877 and ASTM D1816 methods are widely accepted methods to determine the dielectric strength of electrical insulating liquids. Both these methods differ in their electrode configuration and the state of the liquid in the cell. ASTM D877 is involved in flat-faced cylindrical electrodes, a standard electrode gap of 2.5 mm while ASTM D1816 is performed with spherically shaped electrodes at a distance of 1 mm and/or 2 mm. ASTM D1816 is equipped with a head motor stirrer on the test cell to facilitate a gentle stirring motion of the liquid in the test cell. However, it is mentioned that ASTM D1816 is the best method to evaluate the dielectric strength of a transformer insulating liquid due to the more representative electric field generated with a spherical electrode configuration. There is a scope for the removal of ASTM D877 evaluation method for the evaluation of dielectric strength for transformer insulating liquids. Experience has shown that the dielectric strength of paper impregnated in natural ester is almost the same as the one of mineral oil. However, for natural ester, the solid insulation impregnated with ester must necessarily have a relatively higher dielectric strength than that impregnated with mineral oil before being applied in large transformers [10], [11]. Similarly, impulse breakdown is evaluated as per ASTM D3300 for both the liquids with understanding the presence of point-sphere electrode configuration of the transformer materials and aging byproducts. Due to the higher viscosity of ester liquids, due attention is to be laid to avoid the water bubble trappings within the test cell.

Thus, to avoid trapped microbubbles of air in the insulating liquid due to a breakdown, a minimum or equal to 15 minutes (at room temperature) of the time gap is to be maintained from the instant the liquid is filled in the test cell. This may also be applicable to the time gap to be maintained between repeated breakdowns during experimental studies of ester fluids. Gassing tendency is evaluated as per ASTM D2300 for natural ester and mineral oils. The gassing tendency of esters and mineral oils at various fault conditions is different. The aging factor of the insulation also play a phenomenal role. The gassing tendency of esters and mineral oils at different faults and different aging conditions are reported in references [12], [13]. The dielectric dissipation factor is directly correlated to the measurement of the polarity of the molecules in the oil. The comparison cannot be made directly between these two liquids because the mechanisms are different. Indeed, the polarity of the triglyceride molecules present in natural ester leads to a slightly higher dissipation factor than mineral oil [14]. The formation of acids caused by intermediate species in mineral oil is due to an increase in its dissipation factor. For natural ester, this elevation varies only according to its internal ester linkages. An oxidation reaction ensues, and increases more its acidity, resulting in an increase of the dissipation factor. It is therefore important in monitoring to consider the rate of change of the dissipation factor, unlike the absolute value. Significant electrical properties and their evaluation methods for both the liquids have been summarized in Table 1.

TABLE 1. Evaluation of electrical properties for acceptance of a new liquid.

S. No	Property	Mineral oil IEEE Std C57.106 [3]	Natural Ester IEEE Std C57.147 [8]
1	Dielectric breakdown voltage	ASTM D1816, ASTM D877	
2	Dielectric breakdown impulse voltage	ASTM D3300	
3	Dissipation factor and relative permittivity	ASTM D924	
4	Gassing tendency under electrical stress	ASTM D2300	
5	Volume resistivity	-	ASTM D 1169

2) PHYSICAL PROPERTIES

The physical parameters of an insulating fluid must be evaluated from time to time to understand the insulating liquid's degradation. Interfacial tension and color are the vital physical characteristic parameters of an insulating liquid to access the level of contamination [15]. Interfacial tension is one of the widely accepted aging markers for mineral oils, and its application to ester liquids is challenging due to the polar molecular structure of the ester group. However, understanding the color number and interfacial tension is essential to understand the degree of contamination of the insulating liquid. The detrimental limiting values of interfacial tension will be different for ester and mineral insulating liquids due to the difference in the molecular structures. To understand the risk of fire associated with the insulating liquids, fire point, and flash point are evaluated. The risk of fire in mineral oil-filled transformers may be accessed directly with the measurement of fire point and flashpoint. In the case of ester liquids, these properties are to be used for understanding the response of the liquid to heat and flame under controlled laboratory conditions. Evaluation of fire and flash point to decide with the fire risk assessment of in-service ester-filled transformers is not recommended. This is because esters react to heat and flame at a higher temperature as compared to mineral oils [16]. Therefore, the risk assessment and maintenance of ester-filled transformers should not be confined to the higher fire and flashpoints alone. The pertinent assessment of other related parameters may also be monitored accordingly to understand the risk associated with the ester filled transformers. Significant physical properties and their evaluation methods for both the liquids have been summarized in Table 2.

Pour point, and kinematic viscosity are another set of challenging physical properties with ester liquids that are to be understood. With reduction in temperatures, viscosity is of the ester group is found to be higher than mineral insulating oils [17]. Thus, influencing the liquid fluidity with reduction in temperatures. Pour point is the temperature below which liquid starts freezing while influencing the liquid fluidity. It is reported that, the pour point may be influenced by

TABLE 2. Evaluation of physical properties for acceptance of a new liquid.

S. No	Property	Mineral oil IEEE Std C57.106 [3]	Natural Ester IEEE Std C57.147 [8]
1	Interfacial tension	ASTM D971	
2	Color	ASTM D1500	
3	Aniline point	ASTM D611	-
4	Fire point and flashpoint	ASTM D92	ASTM D92 (open cup method)
5	Pour point	ASTM D97	ASTM D97, ASTM D 5949, ASTM D5950
6	Visual examination	ASTM D1524	
7	Relative density	ASTM D1298	
8	Kinematic viscosity	ASTM D445 ASTM D2161	ASTM D445

the effect of viscosity or previous thermal history of the specimen [18]. It is to be noticed that viscosity increase is attributable to the oil contamination and oxidation rates while pour point is least attributable to the degradation aspects and undergoing process. Further, in a transformer operating at lower temperatures, the reduction in liquid fluidity is attributable to the average temperature for a definite time period, rather than the lowest recorded temperature. Hence, traditional viscosity measurements around pourpoint temperatures may be confusing for comparing with the transformer liquid specimen. This is because of the significant difference in the volume of the liquid in the real transformer and the specimen volume used to measure viscosity and pour point [18], [19]. Higher viscosity is generally noticed by the interaction of the oil with atmospheric air (or oxidation) and will polymerize the insulating liquid. It is to be ensured that natural ester filled unit is not left de-energized for a longer time. These conditions play a very critical role for especially ester-filled transformers in cold climatic regions. Meanwhile, the density of the oil may not be pertinent to the degradation evaluation; rather, it will provide an idea on the formation of free water or floating ice crystals in the transformers when reached less or equal to 0°C. Thus, the agreement between the viscosity-loading guide-pour point is to be strictly followed as per the manufacturer's recommendation. This factory guideline is also to be respected while selecting the type of transformer. An important challenge concerns the impregnation of blocks with natural ester. The viscosity of a fluid is one of the important parameters that affect the impregnation result of the solid insulation (paper, pressboard and blocks). Comparative experimental studies on the block impregnation process with natural esters and mineral oils shown that increase in the fluid temperature, decreases the viscosity and hence reduces the impregnation time of the blocks [20]. It is therefore essential for the manufacturer to determine the accurate temperature and time for impregnation.

3) CHEMICAL PROPERTIES

Chemical properties are unique integral properties for any insulating liquid that are sensitive to degradation, temperatures, and operating environment. It is to be recalled that mineral insulating oils and ester dielectric fluids belong to a completely different chemical group. Thus unlike, electrical and physical properties, chemical properties differ on a wide spectrum for ester and mineral insulating liquids. Also, chemical properties like water content, acidity, gassing tendency, and oxidation stability are important diagnosing aspects for liquid-filled transformers. Therefore, in the present section, differences in assessment, behavior, and influence of the said chemical properties have been discussed. Water content in transformer insulating liquids is detrimental to the life of the transformer, and unfortunately, the presence of water in oil/paper insulation is unavoidable. Presence of water content in oil affects the dielectric breakdown of any insulating liquids. Thus, there is a need to understand the hydrolysis, hydrophilic/hydrophobic nature, and water saturation behavior of insulating liquids. Esters are hydrophilic in nature and actively participate in hydrogen bonding as hydrogen-bond acceptors. This ability confers esters to have high water solubility, leading to higher water saturation (depending on the temperature, 20-30 times more) than mineral insulating oils [21]–[23]. In addition, the rate of hydrolysis of ester group is higher than that of the mineral oils, and consequently, more moisture is absorbed in this process [24]. This leads to the formation of the long-chain fatty acids, which elevate the liquid's acid number. Similarly, the pyrolysis of cellulose insulation in ester produces a similar kind of acids (long-chain).

As more moisture is dissolved in esters, the pyrolysis rate will be less than mineral oils. It is to be recalled that, the strength of an organic acid is inverse with the chain length. Thus, the long-chain fatty acid formed in esters are weak and are not detrimental to the insulation system. However, oxidation of esters produces short-chain fatty acids, which react vigorously with other transformer materials and promote the development of the oxidation products [25]. This is the reason for lesser oxidation stability and polymerization (gelling) of the esters. Further, esters are developed from the fatty acids accumulated in the vegetal seeds and flowers; thus, the acidity of the base ester liquids will be higher than mineral oils. Natural esters have high molecular weight acids compared to mineral oil that contains low molecular weight compounds [8], [25]. Therefore, a higher acidity number of esters is not as detrimental as the mineral insulating oils. The influence of acids in mineral oils and ester oils generated due to hydrolysis is summarized in Figure 1. It is also to be mentioned that there will be a significant difference in the oxidation process any bulk volume of fluid to the thin film oxidation. It is established that oxidation is vigorous on the surface that is exposed to air. Thus, thin films exposed to air is of greater concern to that of the bulk liquid in the tank [8]. It is experimentally verified that, bulk volume of natural ester stored in uncovered tank or pool is less affected by the oxidation when compared to the thin films (impregnated by natural esters) [26]. However, different fluids may have

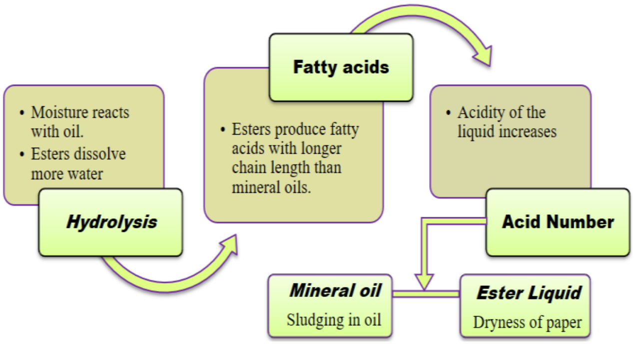


FIGURE 1. Perspective of the hydrolysis and acid formation.

different safe exposure times and associated actions that are to be followed as per the proprietary recommendations.

It is inferred that; higher acidity of esters may be otherwise understood as a degree of dryness of the insulating paper whereas higher acidity in mineral indicated the formation of sludge in the oil [14]. Hence, one may consider the acid number of mineral oils to decide with the reclamation and replace action while acid number alone is not capable of deciding this action in the case of ester liquids. The resistance to oxidation of natural esters is lesser than that of the mineral oils. Thus, natural ester is not recommended for breathing units, bladderless units, and thin-filmed surfaces. However, ester fluid manufactures have emphasized this issue in recent years. The surface of the natural esters polymerizes with continuous exposure to the air. This may possibly increase the liquid viscosity, initiate gelling, and reduce cooling capabilities. The relationship with the exposure time of natural ester (liquid surface and thin film) to air and polymerization is still a challenge. Different natural esters will have different acceptable exposure limiting times (in case of maintenance); thus, any de-tank maintenance activity for natural ester filled transformers parts may be performed as per the recommendations of the manufacturers. There is no established and approved method for evaluating the oxidation stability of the natural esters. It is mentioned that the existing methods ASTM D2112 and ASTM D2440 have no agreement between the laboratory evaluation and field performance of ester liquids. ASTM D2112 is used as a control test to evaluate the sustainability of the oxidation inhibitors, while ASTM D2440 is applicable for evaluating oxidation inhibitors and the consistency of oxidation stability of mineral insulating oils. However, these methods are not applicable to ester fluids. However, IEC 62770 proposed a test method for evaluating the oxidation stability of natural esters with a modification of heating time to 48 hours. The evaluation methods of the significant chemical properties for both the liquids have been summarized in Table 3.

TABLE 3. Evaluation of chemical properties for acceptance of a new liquid.

S. No	Property	Mineral oil IEEE Std C57.106 [3]	Natural Ester IEEE Std C57.147 [8]
1	Water content	ASTM D1533	ASTM D1533 (KF method)
2	Inhibitor content	ASTM D2668 ASTM D4768	-
3	Corrosive Sulphur	ASTM D1275	
4	Total dissolved gas	ASTM D3612 ASTM D2945 ASTM D3284	ASTM D3612 ASTM D3284
5	Acidity	ASTM D664, ASTM D974	
6	Gassing tendency under thermal stress	ASTM D7150	-
7	PCB content	ASTM D4059	
8	Oxidation stability	ASTM D2440 ASTM D2112	IEC 62770 (48 hours)
9	Furan analysis	ASTM D5837	

B. ACCEPTANCE AND MONITORING

Insulating liquids are factory processed and are later transferred to the transformer customers with due care. The new, unused liquids are mostly shipped in tanks (drums, containers, and rail tanks) and are filled into the transformers at the site. In some cases, the transformer is filled with insulating liquid and are the unit is shipped along with the oils to the site. However, in both cases, due care is to be maintained by the manufacturer in ensuring the liquid's quality to serve as an effective insulant and heat exchanging media. The unused insulating liquids are to be evaluated by the customer before accepting in order to understand the properties of the liquids that are pertained during the shipping. The evaluation methods and accepting limits for unused mineral insulating oils and natural esters should be in accordance with ASTM D3487 and ASTM D6871, respectively. Meanwhile, the waiting time to energize after filling the insulating liquid into the transformer is traditionally the time until room temperature is achieved. In the case of ester-filled transformers, a longer time is required because esters consume higher time to penetrate through the new pressboards. This wait time or standing time is attributable to pressboard type, the thickness of pressboard materials, voltage class of transformer, filling temperature of liquid and ambient temperature. For the distribution transformers, 8 hours to 24 hours waiting time is recommended, while for power transformers, a minimum of 24 hours waiting time is advised. However, manufacturer recommended standing time is to be preferred if such information is provided. Later the liquid is to be evaluated before energizing the transformer. In cases where the evaluation of the new insulating liquids (shipped for filling in the units at the site) is not completely possible as per ASTM D3487/ASTM D6871, the minimum tests and the corresponding limiting values that need to be performed are summarized in Table 4.

As discussed earlier, in some cases, shipment is made while the oils are filled in the transformers. In this case, the insulating liquid is to be sampled from the transformer and is to be evaluated before the transformer is energized. It is to be mentioned that, sampling procedure for mineral oils and

TABLE 4. **Acceptable limits for unused shipped Liquids.**

S. No	Property/Standard	Mineral oil IEEE Std C57.106 [3]	Natural Ester IEEE Std C57.147 [8]
1	Breakdown voltage (kV; minimum), ASTM D1816	1 mm gap=20 2 mm gap=35	**Bulk container**: 1 mm gap=20 2 mm gap=35 **Drums** 1 mm gap=35 2 mm gap=60
2	Impulse voltage (kV, minimum), ASTM D3300	-	25.4 mm gap, 25°C =130
3	Dissipation factor (%maximum), ASTM D8924	25°C =0.05 100°C =0.30	25°C =0.2 100°C =4.0
4	Interfacial tension (mN/m; minimum), ASTM D971	40	-
5	Color (maximum), ASTM D1500	0.5	L1.0
6	Visual examination ASTM D1524	Bright and Clear	-
7	Acidity (mg KOH/g; maximum), ASTM D974	0.03	0.06
8	Water content (Mg/kg; maximum), ASTM D1533	35	Bulk container: 200 Drums: 100
9	Oxidation inhibitor (%, maximum), ASTM D2668	Type 1 oil=0.08 Type 2 oil= 0.3	-
10	Corrosive Sulphur ASTM D1275	Non-corrosive	-
11	Relative density (maximum), ASTM D1298	15°C = 0.91	25°C = 0.96
12	Flash point (°C; minimum), ASTM D92	-	275
13	Fire point (°C; minimum), ASTM D92	-	300
14	Pour point (°C; maximum), ASTM D97	-	-10
15	Kinematic viscosity (mm^2/s; maximum), ASTM D445	-	0°C =500 40°C =50 100°C =15

ester liquids is to be performed as per ASTM D923 unless any special manufacturer requirements are mentioned. The limiting values for insulating liquids filled and shipped along with the transformers before energizing are tabulated in Table. 5 for different voltage classes. In any case, a minimum of breakdown voltage, interfacial tension, water content, and dissipation factor are important parameters for the acceptance of mineral oils.

Degradation of an insulating system is preliminarily initiated due to the presence of oxygen, water, and temperature. It is to be understood that the presence/occurrence of these factors is unavoidable, and hence manufacturers of mineral oils consider the inclusion of inhibitors with allowable limits. Hence, it is important to evaluate the liquid properties to ensure the continuity of the liquid for service. In view of the above-said reasons, protecting the pristine liquid conditions is not possible, and all efforts are required to evaluate and maintain the conditions that are close to pristine conditions while being in-service. Generally, aged oil may be classified into three classes, Class I (liquid may be acceptable to continue use), Class II (liquid may be questionable to continue use), and Class III (liquid may be not acceptable to continue use). A clear availability of limiting values for different classes for ester-filled transformers is still a challenge. However, the acceptable limits to continue using the liquids in service have been summarized for different classes in Table 6.

The similarities and differences in evaluation methods of various properties from the target IEEE standards are discussed above. In most cases, the tests used to evaluate mineral oils are also used to evaluate natural esters. However, the interpretation and the meaning of the results are different since the chemistries of the two types of liquids are very different. Therefore, the evaluation methods that were previously applicable only for mineral oil and are now applicable are listed below.

- ASTM D971: Standard test method for interfacial tension of oil against water by the ring method. Because of the high hydrophilic nature of natural esters when new, the interfacial tension is lower when compared to mineral oils (the highest values are in the mid-20s mN/m) [27]–[29]. Under service conditions, acids and

TABLE 5. Acceptable limits obtained from [3] and [8] for unused liquids received in equipment before energizing.

	Voltage class	**≤69kV**		**>69kV to <230kV**		**≥230kV**	
S. No	**Property**	**MO**	**NE**	**MO**	**NE**	**MO**	**NE**
1	Breakdown voltage (kV; minimum)	1 mm gap=25 2 mm gap=45		1 mm gap=30 2 mm gap=55		1 mm gap=35 2 mm gap=60	
2	Dissipation factor (%maximum)	25°C =0.05 100°C =0.40	25°C =0.5	25°C =0.05 100°C =0.40	0.5	25°C =0.05 100°C =0.30	0.5
3	Interfacial tension (mN/m; minimum)	38	-	38	-	38	-
4	Color (maximum)	1.0	L1.0	1.0	L1.0	0.5	L1.0
5	Visual examination	Bright and clear					
6	Acidity (Mg KOH/g; maximum)	0.03	0.06	0.03	0.06	0.03	0.06
7	Water content (Mg/kg; maximum)	20	300	10	150	10	100
8	Oxidation inhibitor (%, maximum)	Type 1 oil=0.08 Type 2 oil= 0.3	-	Type 1 oil=0.08 Type 2 oil= 0.3	-	Type 1 oil=0.08 Type 2 oil= 0.3	-
9	Corrosive Sulphur	Non-corrosive	-	Non-corrosive	-	Non-corrosive	-
10	Fire point (°C; minimum)	-	300	-	300	-	300
11	Kinematic viscosity (mm^2/s; maximum)	-	50	-	50	-	50
12	Total dissolved gas	N/A	-	N/A	-	0.5%	0.5%

TABLE 6. Acceptable limits obtained from [3] and [8] for continued use of in-service liquids for different voltage classes.

	Voltage class	**≤69kV**		**>69kV to <230kV**		**≥230kV**	
S. No	**Property/Liquid**	**MO**	**NE**	**MO**	**NE**	**MO**	**NE**
1	Breakdown voltage (kV; minimum)	1 mm gap=23 2 mm gap=40		1 mm gap=28 2 mm gap=47		1 mm gap=30 2 mm gap=50	
2	Dissipation factor (%maximum)	25°C =0. 5 100°C =5.0	25°C =0.5	25°C =0. 5 100°C =5.0	0.5	25°C =0.5 100°C =5.0	0.5
3	Interfacial tension (mN/m; minimum)	25	-	30	-	32	-
4	Acidity (Mg KOH/g; maximum)	0.20	-	0.15	-	0.10	-
5	Water content (mg/kg; maximum)	35	450	25	350	20	200
6	Oxidation inhibitor (minimum)	Type 2 oil= 0.08%	-	Type 2 oil= 0.08%	-	Type 2 oil= 0.08%	-
7	Fire point (°C; minimum)	-	300	-	300	-	300
8	Kinematic viscosity (mm^2/s; maximum) *initial value (IV)*	-	≥10% from IV	-	≥10% from IV	-	≥10% from IV

polar compounds will decrease the interfacial tension. While limits are well established for MO, investigations are still needed to establish limits for new or in-service ester-based liquids.

- ASTM D1533: Standard test method for water in insulating liquids by coulometric Karl Fischer titration.
- ASTM D1816: Standard test method for dielectric breakdown voltage of insulating oils of petroleum origin

using VDE electrodes. This method is applicable for natural ester with an increase the resting time prior to the first breakdown.

- ASTM D2440: Standard test method for oxidation stability of mineral insulating oil. This method is applicable for natural ester if heating time is reduced to 48 hours.

Currently, the standard IEC 62021-1 used to determine the acidity in mineral oils is also applied to natural esters. The maximum acidity limit value for in-service natural esters with voltage class <69 kV is 0.3 mg KOH/g [30]. There is no indication in the literature for voltage classes > 69 kV. Some authors have shown that the acidity of esters increases proportionally overtime, and this increase could extend well beyond the specified limit value, even in an enclosed environment with minimal oxygen. [30], [31]. Better aging performance of cellulose has been found in natural ester with a high level of acidity compared to mineral oil [30]. In addition, the differences in the acidity levels and oxidation rates of mineral oils and natural ester liquids are challenging aspects too. However, the limits for the acidity have been established but the optimal weights and types of the acceptable oxidation inhibitors are to be determined. The widely accepted oxidation inhibitors for mineral oils are 2,6-ditertiary-butyl phenol (DBP) and 2,6-ditertiarybutyl para-cresol (DBPC). ASTM 2668, *"Standard test method for 2,6-ditertiarybutyl para-cresol and 2,6-ditertiary-butyl phenol in electrical insulating oil by infrared absorption*" is used for direct estimation the said inhibitors in mineral oil. In case of natural esters, the manufacturers blend pertinent proprietary inhibitors to the liquid. Therefore, specific inhibitor content evaluation testing techniques will be required for ester-filled transformers.

III. DISSOLVED GAS ANALYSIS (DGA) AND DIAGNOSIS

Dissolved gases in insulating liquid are normally formed due to the decomposition of insulation liquid and solid insulation. The decomposition of the insulation system is occurred due to several reasons with main factors, including thermal and electrical fault conditions. As the chemical composition of mineral insulating liquids and ester liquids is different, the gassing tendency of both the liquids is different. Even if the type of gasses generated for different fault conditions (electrical and thermal) are the same, the detrimental levels of different gas concentrations will be different for different liquids. Therefore, IEEE Std C57.104 and IEEE Std C57.155 are adopted for understanding dissolved gases generated in oil-filled transformers and ester (natural and synthetic) filled transformers, respectively. Nevertheless, as the type of gasses generated for similar faulty conditions are the same in both mineral and ester liquids, the same sampling and test methods are applicable. In addition, the information provided in IEEE Std C57.155 is mostly based on laboratory experienced database and limited-service experiences. This is due to the limited in-service experience database for ester fluids. The critical limits mentioned in IEEE Std C57.104 are derived from numerous service experience of mineral oil that is gained over the years. The conclusions in the IEEE Std C57.155 are reported from limited sources.

Hence, the data provided by the manufacturer, the new and in-service history of the same unit may always be preferred. It is to be mentioned that, the effect of the stray gassing in ester fluids is to be laid emphasize in order to avoid masked interpretations of the dissolved gasses. The evaluation of stray gassing is evaluated as per ASTM D7150 at 120 °C. It is reported that ethane is produced in the ester group liquids under normal conditions too. This stray gassing is seen high in the initial times and is settled over time. The generation of ethane is sensible to oxygen, light, and heat; thus, care should be taken in handling, storing, and accepting new ester liquids. In addition, stray gassing of ethane may reach several 100 ppm and must be considered to establish the baseline or signature of a transformer.

In IEEE C57.104, concentrations of individual and total dissolved combustible gasses have been used for identifying the risk associated with incipient internal faults. Whereas, in IEEE C57.155 the gas rate limits discussed are applicable only when no previous history is available and is for reference purposes only. However, the annexures included in IEEE C57.155 presents experimental experiences and comparison with various oils. Interpretation of dissolved gasses for mineral oils has been presented in IEEE C57.104 using Rogers ration method and Doernenburg ratio. Further, to advise the diagnostic action, four cases have been identified with different individual gas values. Also, to understand the gas in the air phase Ostwald solubility coefficient of various gasses has been presented. In IEEE C57.155, interpretation and diagnosis have been majorly emphasized on Duval's fault gas analysis. Thus, there is a lot of scope for developments in the existing standards concerning the fault diagnosis of ester-filled transformers, and there is also a need to understand the influence of the aging markers on the gas trending. The summary of the gases for various fault conditions has been summarized in Table 7.

IV. RECLAMATION OF AGED OILS

Reclamation of aged oils is performed to remove the products that are developed in the insulating liquids because of the service aging. The byproducts of aging may be but not limited to acids, cellulose decay particles, colloids, polar solvents, water content, dissolved gasses, sludge/ contaminants, and other transformer materials [32], [33]. Insulating liquids may be subjected to reconditioning, reclamation, or replacement based on the status of oil health, service life, and financial conditions. It is to be understood that, treatment of insulating liquids may also remove desirable additives such as inhibitors; thus, evaluation and addition of new components is required after the treatment.

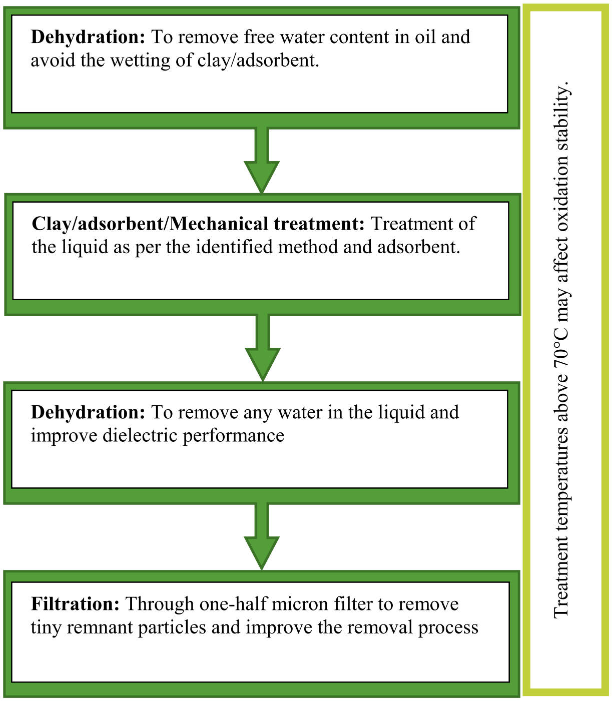
Reconditioning of insulating includes dehydration and degassing; this is mostly performed when dissolved gassing

TABLE 7. Details of dissolved gases for various fault conditions.

Fault	IEEE Std C57.104 [4]	IEEE Std C57.155 [9]
Cellulose Decomposition	• CO and CO_2 gases are generated with the decomposition of the cellulose. The ratio CO_2/CO is used as a key marker for this type of fault. • Principal gas: carbon monoxide.	• CO and CO_2 gases are generated with the degradation of the cellulose. The ratio CO_2/CO is used as a key marker for this fault. • Below 400°C–450°C, hydrocarbon gases represent the overheating of cellulosic insulation. • Above 400°C–450°C, the production of carbon oxides by decomposition of ester liquid will be confused with the CO and CO_2 generated due to cellulose degradation. • Therefore, the corresponding acid number and ethylene concentration may be accessed to identify the source.
Overheating	• H_2, CH_4, C_2H_4, C_2H_6 and C_2H_2 (increases with an increase in temperature). • Principal gas: ethylene.	• H_2, CH_4, C_2H_4, C_2H_6 are generated below 400°C. Traces of C_2H_4 and C_2H_6 is witnessed between 400°C to 600°C. C_2H_2 is noticed if the temperature is above 600°C.
Low energy electrical (corona/partial discharges)	• H_2 is predominantly observed due to partial discharges. • Small quantities of CH_4 and traces of C_2H_2 are observed due to partial discharges. • C_2H_2 and C_2H_4 concentrations increase with an increase in the intensity of the discharging activity. • Principal gas: hydrogen.	• H_2 is predominantly observed due to partial discharges. • Small traces of CH_4, C_2H_6, C_2H_2 are observed if partial discharges persist for a long time.
High energy electrical (arcing)	• H_2, CH_4, C_2H_4, C_2H_2, CO, and CO_2 are generated during high-energy discharge activity. • The concentration of C_2H_2 and C_2H_4 rises significantly for high-intensity faults. • If the associated temperature reaches 700°C to 1800°C, C_2H_2 concentration increases and is of high risk to the transformer. • Principal: C_2H_2.	• H_2, CH_4, C_2H_4, C_2H_2, CO, C_2H_6, and CO_2 are generated during high energy discharge activity.

or water content is more while other parameters are in the acceptable limits. Reclamation of insulating liquids is emphasized on the removal of acids, sediments, and contaminants by suitable adsorbents or mechanical agitations [34]. The details of the various treatment process for mineral insulating oils have not been discussed in this section due to pagination and documentation lengths. As per IEEE Std 637, the gravity-percolation method is suitable for the static treatment process (treatment plant is fixed, and oil is brought from different units), and portable pressure percolator treatment is suited for dynamic treatment process.

However, as per IEEE Std C57.147 magnesium aluminum phyllosilicate, magnesium silicate activated alumina, and in addition, the mixture of these adsorbents may also improve the removal performance. The determination of an effective adsorbent and treatment process for ester liquids is still a challenge. Despite any clay/adsorbent and any treatment process, the following process shown in Figure 2 is to be essentially followed during the reclamation process of both ester and mineral insulating liquids. It is to be noted that, treatment temperature of above 70°C for mineral insulating oil hampers the oxidation stability. The same may be applicable for the treatment of ester fluids unless the manufacturer mentions a specific temperature. In addition, the choice of reconditioning and reclamation limits are not established and is attributable to use discretion or manufacturer recommendations. Further, the choice of



Dehydration: To remove free water content in oil and avoid the wetting of clay/adsorbent.

Clay/adsorbent/Mechanical treatment: Treatment of the liquid as per the identified method and adsorbent.

Dehydration: To remove any water in the liquid and improve dielectric performance

Filtration: Through one-half micron filter to remove tiny remnant particles and improve the removal process

Treatment temperatures above 70°C may affect oxidation stability.

FIGURE 2. Procedure for reclamation of transformer insulating liquids.

adsorbents and treatment methods is another challenge and the same maybe in the agreement of the manufacturer and the customer. This depends on several factors like cost, availability of treatment equipment, treatment materials, and labor.

V. CONCLUSION

Over the years, insulating liquid has become a key concern for the condition monitoring engineers in ensuring proper maintenance of liquid-filled transformers. Meanwhile, biodegradable insulating liquids are established to be a potential choice for transformer insulation technology. Several utilities across the globe have started using these new insulating liquids for new transformers while a few are retro filled. Different normative have been outlined for mineral and ester insulating liquids due to the phenomenal difference in the chemistry. Therefore, there is a need to understand the commonalities, differences, and challenges following the existing imperative standards of both the insulating liquids. In this article, efforts are made to analyze and summarize the significant IEEE standards concerning acceptance, condition monitoring, diagnostic, and reclaiming aspects. The present analysis is important for researchers and industry for further improvement of the norms, and effective maintenance of ester-filled transformers.

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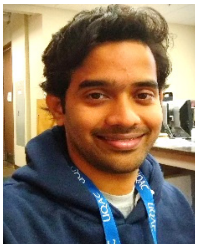

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