High Voltage

Research Article

Influence of ageing on oil degradation and gassing tendency under high-energy electrical discharge faults for mineral oil and synthetic ester

eISSN 2397-7264
Received on 13th October 2019
Revised 11th March 2020
Accepted on 28th April 2020
E-First on 29th May 2020
doi: 10.1049/hve.2019.0291
www.ietdl.org

L. Loiselle[1]*, U. Mohan Rao*[1] ✉*, I. Fofana*[1]

[1]*Research Chair on the Aging of Power Network Infrastructure (ViAHT), Université du Québec à Chicoutimi, Chicoutimi, QC, G7H 2B1, Canada*

✉ *E-mail: mohan.ungarala1@uqac.ca*

Abstract: In this work, mineral oil and synthetic esters were selected at different ageing factors (based on acidity values). Fresh and aged oils have been subjected to high-energy discharges (repeated 100 breakdowns) to simulate electric faults of highly vulnerable intensity. The intent of this work is to understand the influence of high-energy electric faults on oil degradation and gassing tendency at different ageing conditions. In this study, the influence of the high-energy discharges on degradation and gassing tendency at different ageing factors is reported for mineral oil and synthetic esters. Oil degradation is reported by adopting ultraviolet spectroscopy, turbidity and particle counter as per american society for testing and materials (ASTM) standard test methods. Gassing tendencies and fault gas analysis are understood by dissolved the gas analysis using Duval's triangle and Duval's pentagon methods for mineral and non-mineral oils. It is found that the influence of high-energy discharges on oil degradation is higher in mineral oils to that of the synthetic esters. The intensity of the gassing tendency is higher for ester fluids; however, as per the Duval methods, the faulty conditions are at lower levels as compared to mineral oils.

1 Introduction

Insulation degradation in oil-filled transformers is one of the main concerns for condition monitoring engineers. It is known that the transformer failure rate and service life are mostly governed by the insulation system [1]. There are several factors responsible for insulation deterioration, out of which, the heat liberated from core-winding assembly and electrical discharges play a vital role [2]. It is known that electrical stress and thermal stress expedite the degradation rate of oil–paper insulation. Subsequently, this early degradation leads to failure of the insulation system and hence premature ageing of the transformer. Thus, careful monitoring of the degradation rate and appropriate condition monitoring actions are essential for the successful operation of the transformers. This allows the utility and engineers to meet the designed life while leading to efficient asset management [3, 4].

The influence of ageing on oil/paper insulation deterioration is generally understood by simulating an accelerated ageing factor which expedites the deterioration rate. This accelerated ageing factor is generally achieved by either thermal or electrical stressing in the laboratory environment. To date, various researchers reported the influence of ageing on oil degradation parameters for mineral insulating oils [5]. Meanwhile, in understanding the behaviour of alternative insulating fluids, several authors reported the degradation behaviour of synthetic esters (SEs) vis-à-vis mineral insulating oils [6–8]. It is found that the degradation aspects of SEs are better than that of the mineral insulating oils. Importantly, numerous researchers are affirmative towards accepting SEs as a potential alternative for transformer insulation.

Meanwhile, any sudden electrical discharges and thermal hotspots may influence the oil properties and involve in generating different fault gasses. This influence on properties and gassing tendency of the oils is highly attributed to the deterioration level and type of the insulants (oil and paper). In other words, the effect of electrical discharges and hotspots will not be the same for mineral oil (MO) or ester fluids at different ageing conditions. Also, the degree of impact will be dependent on the energy of discharge (high and low), duration of discharge, and temperature of the hotspot. High-energy discharges are mainly due to arcing caused by short-circuiting faults and winding deformations. These discharges involve the excessive generation of hydrogen and acetylene with traces of methane and ethylene. If this fault occurs in cellulose insulants, carbon monoxide and carbon dioxide will also be traced. High-energy discharges are detrimental to the insulation system [9]. High-energy discharges are also associated with high temperatures that may cause premature thermal degradation of oil/paper insulation. Low-energy discharges are mainly due to partial discharges and minor dielectric defects, and these low-energy discharges will involve in the generation of hydrogen, methane, ethane, and ethylene while deteriorating oil/paper insulation [9]. If partial discharges occur within the cellulose insulants, carbon monoxide and carbon dioxide will also be noticed. Hotspots are aroused from severe local overheating caused by loading cycles and internal faults. The sudden temperature raised due to hotspots leads to the formation of gas bubbles along with the deterioration of the oil/paper insulation [10]. Hence, there is a need to understand the influence of high-energy discharges and low-energy discharges separately at different ageing conditions for MO and SEs.

The intent of this research is to understand the influence of the high-energy discharge and low-energy discharge on the degradation level of oil and gassing tendency at different ageing factors. Hence, high-energy discharge and low-energy discharge faults in MO and SEs have been created under laboratory conditions as follows:

i. *High-energy discharge*: repeated breakdowns (100 breakdowns) of the oil by using disk electrodes at a 2.5 mm gap with 2 min of the gap between every breakdown.
ii. *Low-energy discharge*: continues discharge of 9 kV on the surface of the oils for 5 h by using a suitable laboratory model. The results of this study were recently reported by authors group in [11].

Interfacial tension (IFT) and acidity are the widely accepted ageing markers to monitor the degree of insulating fluid deterioration [12]. Peroxides are primary oxidation compounds in insulating liquids and all secondary oxidation compounds (volatile, non-volatile, high molecular weight, and free fatty acid) derived from hydro-peroxide decomposition [13]. Testing techniques used to monitor the level of peroxide in oxidised oil samples include titration,

Table 1 Significant properties of the base oils

Parameters	MO	SE
power factor 50 Hz, 90°C, IEC 60247	<0.001	<0.008
breakdown voltage (kV), IEC 60156	>70	>75
water content (ppm), IEC 60814	<20	50
acidity, IEC 62021	<0.01	<0.03
density at 20°C (kg/dm^3)	0.869	0.97
viscosity (cSt @ 40°C) ISO 3104	9.2	29
fire point (°C) ISO 2592	—	316
flash point (°C) ISO 2719	148	260
pour point (°C) ISO 3016	−54	−56

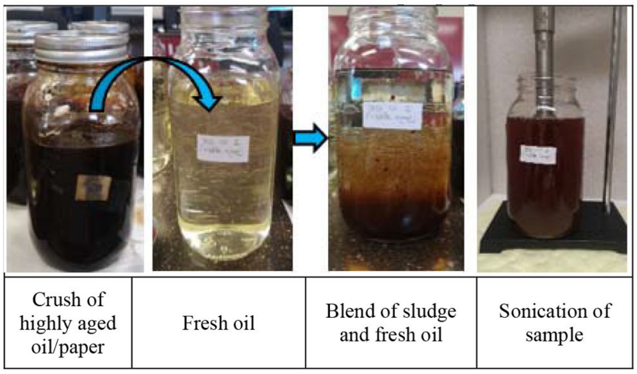

Fig. 1 *Illustration of sample preparation*

Table 2 Oil classification and acidity value as per [16]

S. no	Oil classifications	Neutralisation number
1	good oils	0.0– 0.10
2	Prop. A oils	0.05–0.10
3	bad oils	0.16–0.40

chemiluminescence, electron spin-resonance spectroscopy, ultraviolet (UV) spectroscopy and infrared spectroscopy [13]. Before colloids appear, the first sign will be the drop in the IFT followed by an increase of the total acid number. Both test methods depict a clear correlation. Due to the higher polarity of ester liquids in comparison to MOs, the IFT test gives no meaningful information, presenting low to no variation along with fluid degradation [14]. Therefore, acidity is adopted as an ageing marker for understanding the level of oil degradation. It is to be recalled that there is a direct relationship between acidity, turbidity, and UV absorbance [15]. Therefore, one may monitor the degree of ageing by turbidity, UV spectral curves, and oil absorbance information presented before high-energy discharge in Section 3.

In this paper, the results of a study of the influence of high-energy discharge electric faults on the oil degradation and gassing tendency of MO and SEs for fresh and aged oils are reported. Ageing conditions include Proposition A (Prop. A) class (moderately aged oils) and bad class oils (highly aged oils), which are ensured by acidity measurements [16]. MO and SEs of unused, Prop. A class, and bad class are subjected to repeated high-energy discharges. To understand the oil degradation, dissolved decay products (DDP), absorbance, turbidity, and particle counter measurements are performed as per american society for testing and materials (ASTM) standards. These measurements are performed before and after the discharge simulations. Later, the dissolved gas analysis is performed using Duval triangle and Duval pentagon methods on the oils after repeated high-energy discharge to understand the tendency of gassing at various ageing conditions.

2 Significance and experimental

2.1 Oils and test sample preparation

The properties of MO and SEs adopted for the present study are presented in Table 1. Initially, fresh MO and SEs are subjected to accelerate thermal ageing as per modified ASTM D1934 standard at 115°C with copper (3 g/l) catalyst and cellulose (1:20) in the presence of oxygen. For excessive degradation of the base oils, a large proportion of cellulose kraft papers (1:20) are used. Later after 2000 h degradation, highly degraded and crushed oil/paper insulation is subjected to sonication for 30 s using Qsonica Q1375 Sonicator. This less sonication time is selected to allow protecting the existing oil chemical properties [17].

This sonication helped to make further a fine solution of degraded oil and paper, which is normally treated as sludge and decay content. Later, this decay content is transferred to fresh oil at the appropriate proportions to reach the desired levels of neutralisation number. Finally, the solution of fresh oil and sludge are again subjected to 30 s of sonication followed by 5 min of magnetic stirring to ensure the gentle mixing of the test samples. The process of test sample preparation is presented in Fig. 1.

Fresh and unused oils are used to prepare Prop. A class and bad class oils based on neutralisation numbers. Later, MO and SE of fresh, Prop. A, and bad oils are used for the present experimental studies. The details of the oil classifications are presented in Table 2.

Table 3 and Fig. 2 highlight the details of the acidity measurements performed to ensure Prop. A and bad oil classes for MO and SE.

2.2 High-energy discharge electrical faults

Most of the high-energy discharge faults in a transformer occur in the windings due to turn-to-turn insulation breakdown. This may be due to the dielectric breakdown of the insulation between the turns of the winding. Normally, insulation breakdown occurs due to sudden and high magnitudes of current or voltage, which are higher than the expected or rated values. This breakdown of the insulation results in the flashovers of the winding turns and cause short

Table 3 Oil classification and acidity values

Sample	Acidity test 1 mg KOH/g	Acidity test 2 mg KOH/g	Average	Std. deviation	Class
MO 1	0.0818	0.082	0.0819	0.0001	Prop. A
MO 2	0.2757	0.2675	0.2716	0.0058	bad oil
SE 1	0.1034	0.092	0.0977	0.0081	Prop. A
SE 2	0.2314	0.2573	0.24435	0.0183	bad oil

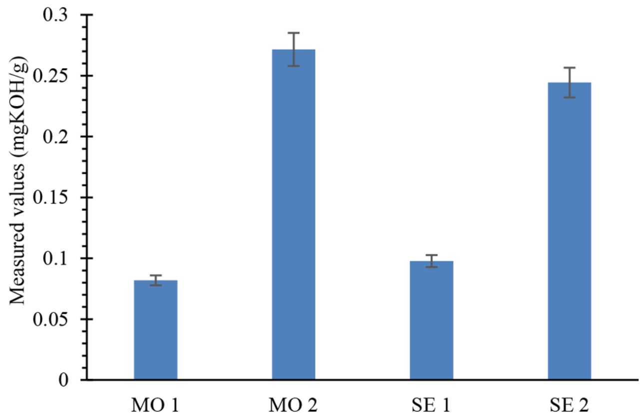

Fig. 2 *Acidity of the oil samples at different oil classes*

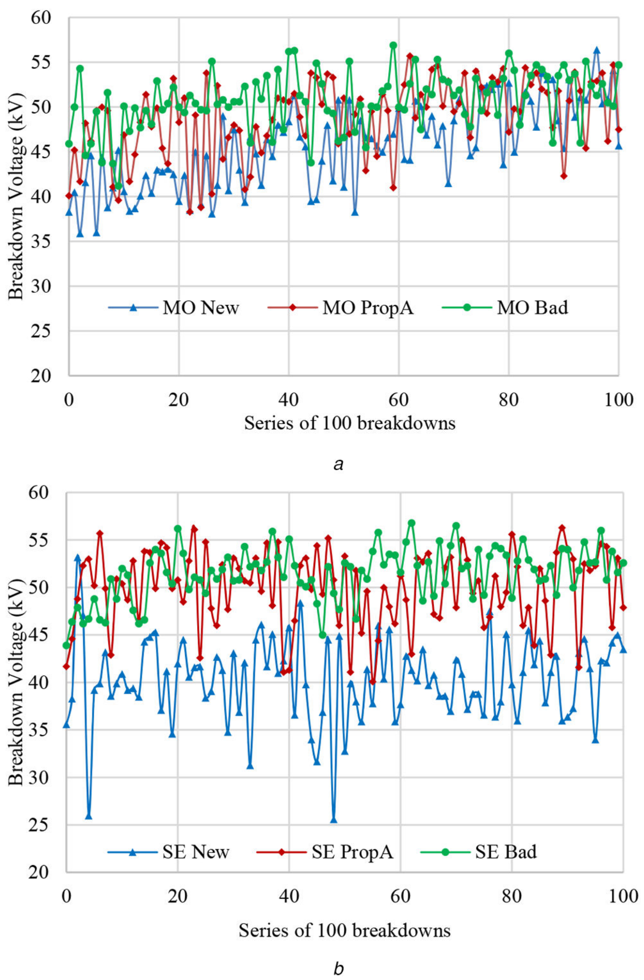

Fig. 3 *Illustration of breakdown voltage values of fresh and aged oils*
(a) For MO,
(b) For SEs

circuits within the winding assembly. These consequences will lead to a severe impact on the insulation system if the fault persists for a long time. These types of faults are witnessed with a significant influence on the integrity of the solid and liquid insulants within the transformer [18]. These faults lead to the generation of contaminants such as water, sediments, and conducting particles, which reduce the dielectric strength of insulating oil. The intensity of the high-energy electrical discharge sometimes turns to continuous arcing that produce a high instant temperature which further degrades the insulation system. These factors cause a pronounced generation of acetylene gas within the oil [18]. According to the key gas method of dissolved gas analysis, the quantity of hydrogen and acetylene is reported to be increased with continuous arcing in the insulation system [9]. Hydrogen will be evolved from cellulose insulants along with traces of carbon dioxide and carbon monoxide if the fault is involved with cellulose insulants.

In the present study, to ensure continuity in the fault, a hundred breakdowns have been created in the laboratory environment as per ASTM D 877 [19] with 2 min gap between every single breakdown. To understand the impact of high-energy electrical discharge faults, oil degradation and dissolved gas analysis have been reported. The series of breakdowns on MO and SE for fresh and aged oils is shown in Fig. 3.

It is to be mentioned that the water saturation limit of an insulating liquid increases with ageing [20]. Since breakdown voltage is relative moisture content dependant [21], at a given absolute moisture content, the breakdown voltage of the aged oil will be higher than the unused one. Under AC stress, a field-induced drift of particles, located in high-field regions, can be entailed by stress relief leading to an improvement of the electrical strength, compared to technically clean oil [22]. Since every breakdown causes definite ageing/degradation of the insulating liquid, this will lead to an increase in the water saturation limit. This is the reason for the increase in the breakdown voltage of oils with elapsing breakdown times and ageing. A statistical analysis conducted by the CIGRE Working Group 12.17 on the root causes of 22 transformers and 40 bushings (765 kV) failures pointed out that attention must be paid to the source and hazard of particles for 400 kV transformers and above [23].

3 Results and discussions

3.1 Influence on oil degradation

3.1.1 UV visible (UV/Vis) spectroscopy (ASTM D 6802): UV/Vis spectroscopy provides an assessment of the concentration of DDP in the aged oil. It is established that the quantity of DDP increases with an increase in the age of oil/paper insulation. This is because the absorbance of the oil to UV and visible rays increases with the increase in the concentration of DDP in the oil.

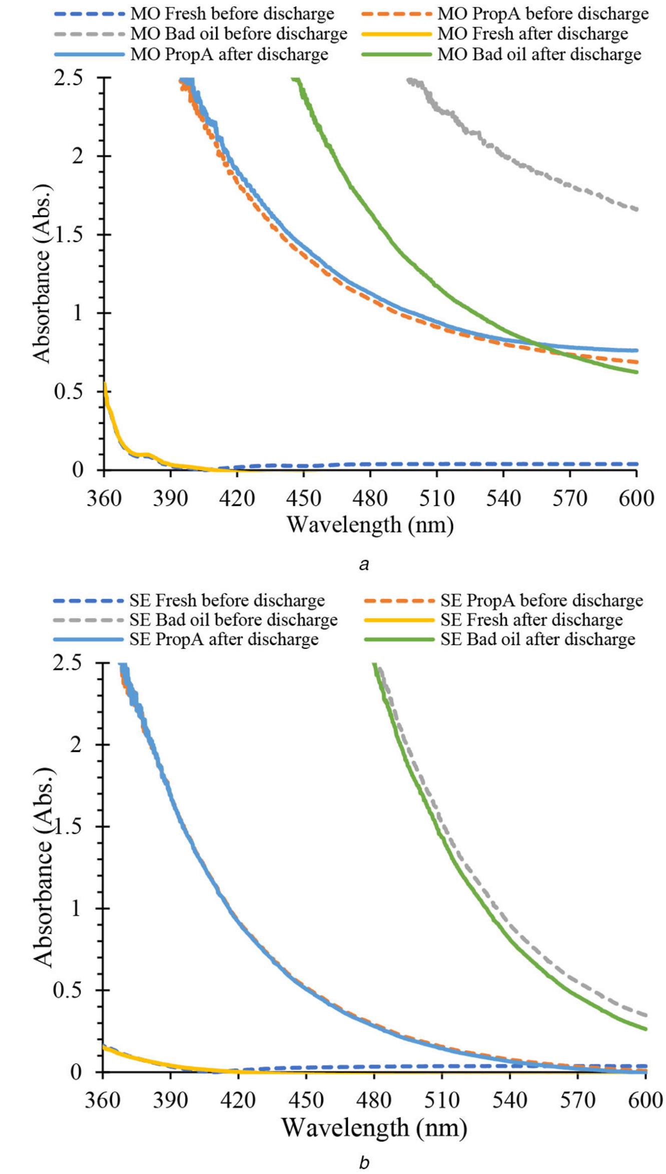

Fig. 4 *UV spectral curves of oils before and after discharges at different ageing conditions*
(a) For MO,
(b) For SEs

Thus, the absorbance curves shift to higher wavelengths. The UV spectral curves of fresh, Prop. A class, and bad class before and after high-energy discharge for MO and SEs are presented in Fig. 4.

It is seen that the concentration of decay content in oils is changed due to high-energy discharge. This is because of the ionisation created by the repeated breakdowns. This repeated breakdown in oil will also allow generating free radicals and oxidising products that deteriorated the insulating oil. It is to be noticed that the shift in spectral curves is significantly low in the case of SEs. This demonstrates the chemical stability of the SE towards high-energy discharge electrical faults. It is also seen that Prop. A class with MO is noticed with a very small deviation. This will not indicate the potential of middle-aged MOs to resist electrical faults. Rather, this may be due to the non-uniform distribution of cellulose particles within the oil samples. To further understand this, absorbance values of MOs and SE fluids are presented in Fig. 5.

The change in the absorbance of oils with ageing and with high-energy electrical faults is seen in Fig. 5. As expected, the absorbance of oils is increasing with the increase in age. However, this change is significantly less in the case of SEs.

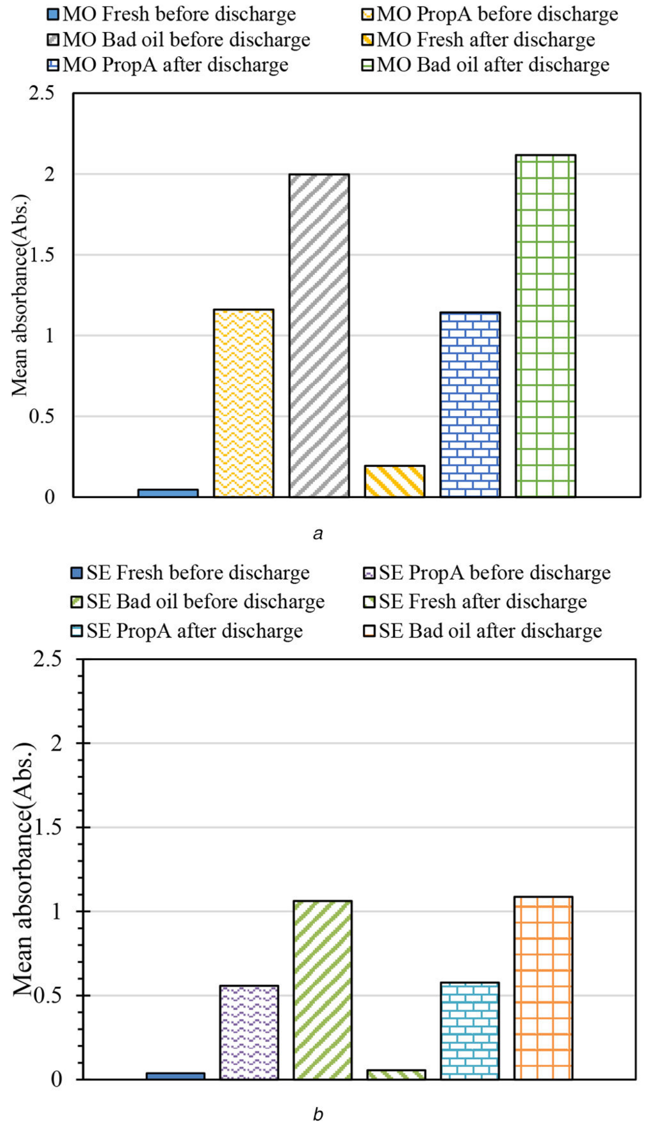

Fig. 5 *Change in absorbance of SE at different ageing conditions for before and after discharge*
(a) For MO,
(b) For SEs

3.1.2 Turbidity (ASTM D 6181): The turbidity of a liquid reveals the ability of the liquid to be transparent. Turbidity is defined as the extent to which the liquid lost its ability to be transparent to light. For transformer oils, turbidity is an important parameter to understand the degree to which the oil is degraded. Owing to the decay particles introduced with ageing reactions, turbidity of transformer oil increases with ageing. In this work, turbidity of fresh, Prop. A class (Prop A), and bad class before and after high-energy discharge for MO and SEs are presented in Fig. 6.

As expected, the turbidity of the fresh oil increases with electrical discharging. This is because of the fact that electrical discharges involve in oil degradation and thus introduce the decay particles in the oil. These decay particles will affect oil transparency to the light. However, the increase in turbidity in the case of fresh SEs is better as compared to fresh MO. It is noticed that the turbidity of Prop. A and bad oils (both mineral and synthetic) increased with respect to ageing. However, the simulation of high-energy discharge in Prop. A and bad class oils leads to a reduction of turbidity for MO and SEs. The possible reason for this reduction could be due to an agglomeration and crumpling of the small-size and large-size decay particles (cellulose particles), respectively. The cellulose particles and decay products in oil may be split or crumple due to sudden and high-energy discharges (100 breakdowns). Also, with increased ionisation in the test cell, there would be a large scope for free

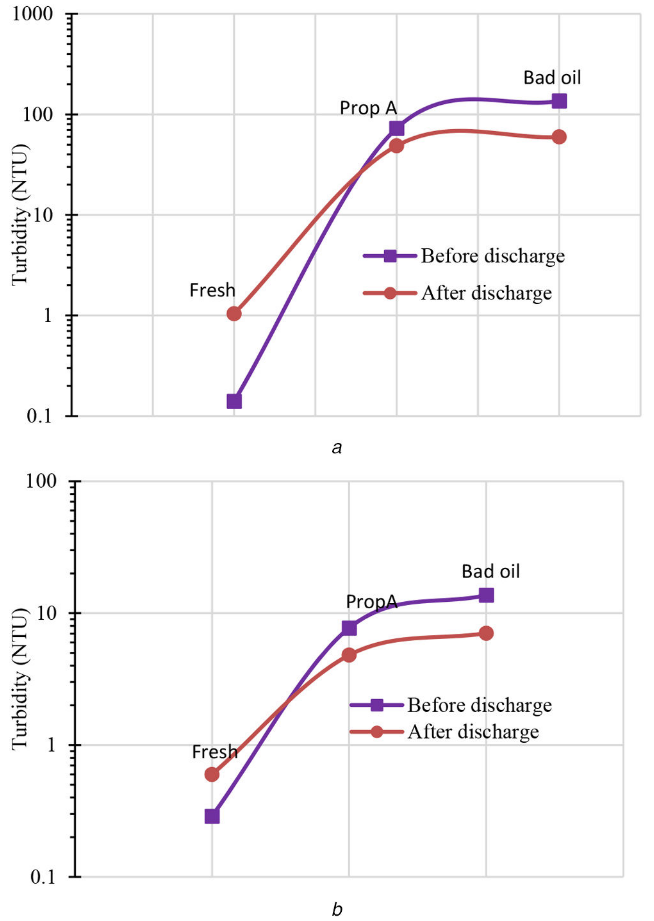

Fig. 6 *Change in turbidity of oils at different ageing conditions for before and after discharges*
(a) For MO,
(b) For SEs

radicles. This phenomenal increase and decrease in turbidity of the insulating oils are foreseen by particle count studies.

3.1.3 Particle count (ASTM D 6786): It is known that decay particles in oil increase with the degradation of oil–paper insulation caused by ageing. The concentration of decay particles is distributed non-uniformly within the available oil volume. These particles have an irregular shape and different sizes. The presence of large-size particles is more detrimental than the presence of small-size particles. However, most of these particles are conductive in nature and increase the dielectric losses of an insulating fluid. Hence, it is essential to understand the presence of these particles as a function of size. In the present study, a programmable particle counter is employed as per ASTM D 6786 to monitor the number of particles present in various oils. The details of particles count for fresh, Prop. A class, and bad class before and after high-energy discharging for MO and SEs are shown in Fig. 7. For fresh MO and SEs, there is a significant increase in the particle count with high-energy discharging (100 breakdowns).

It is to be noted that fresh oils have no cellulose components present in oils, unlike in aged oils. This is the reason why the increase in large-size particles is too low in fresh oils even after discharge simulation. The increase in small-diameter particles is only due to the formation of free radicals and subsequent agglomeration of these free radicals to form decay particles [10]. For aged MO (Prop. A and bad classes), a significant increase in small-diameter particles and reduction of large-diameter particles is noticed. The reduction of large-diameter particles may be attributable to the crumpling or splitting of cellulose particles and agglomerated decay particles under the influence of the high-energy discharges [10]. Further, it is also possible that cellulose particles act as filters or absorbing media under the influence of

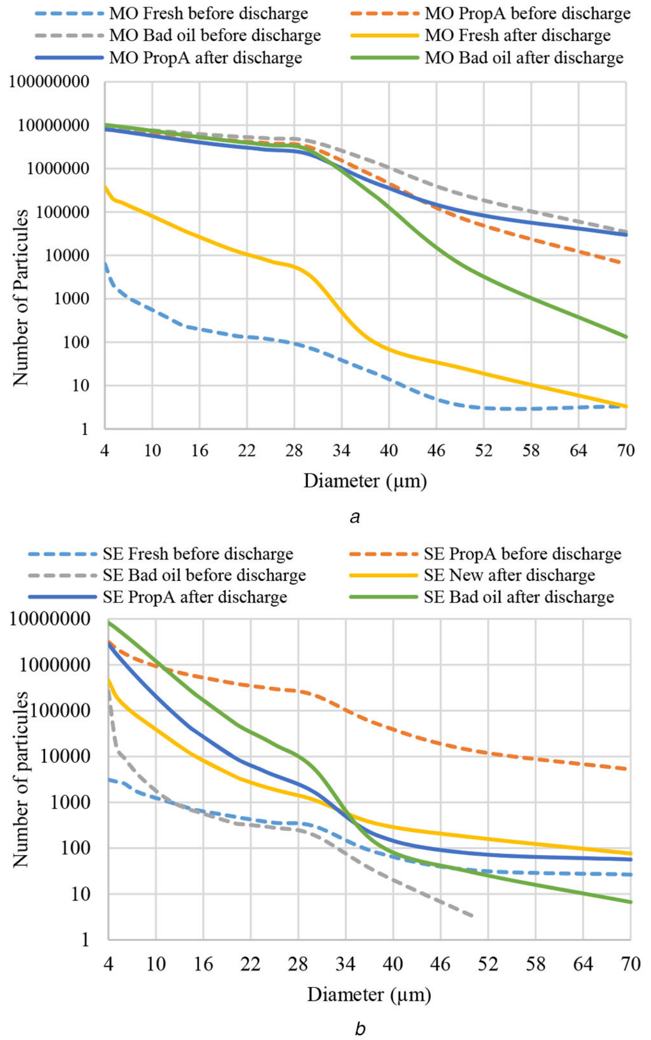

Fig. 7 *Change in the number of particles for SE at different ageing conditions with high-energy discharge*
(a) For MO,
(b) For SEs

electrical discharges and absorb the decay content in certain cases, as reported in [24]. This will certainly lead to an increase in smaller particles which is evident in the above results. Therefore, the increase in smaller diameter particles may be due to the agglomeration of cellulose particles, free radicals, and other decay contents in the oil under the influence of discharge energy. The non-uniformity in the particle distribution with respect to ageing is to be addressed with the artificial addition method adopted to create a different class of oils. Also, the degradation that is occurred in the cellulose insulants will not be uniform even though the degradation conditions are similar. Hence, cellulose insulants play a vital role in the generation of different decay particles and deciding the detrimental factors for the insulation system.

3.2 Dissolved gas analysis

The dissolved gas analysis is a powerful tool to understand the type of gasses generated under the faulty conditions. In the present work, after repeated 100 breakdowns, i.e. high-energy discharge, an oil sample of 30 ml is sampled with a glass syringe from the high-voltage discharge cell. This 30 ml oil sample has been subjected to the dissolved gas analysis to understand the gasses generated due to discharging activity. The per unit (p.u.) values of the dissolved gases are plotted in Fig. 8. In order to have a proper interpretation of the changes, it was decided to plot in p.u. in log scale. It is seen that, for SE, all gases were increased except O_2 and N_2. From the fresh class of oil to bad class of oil: CO_2 increased 4 times, CO increased 44 times, C_2H_6 increased 198 times, C_2H_4

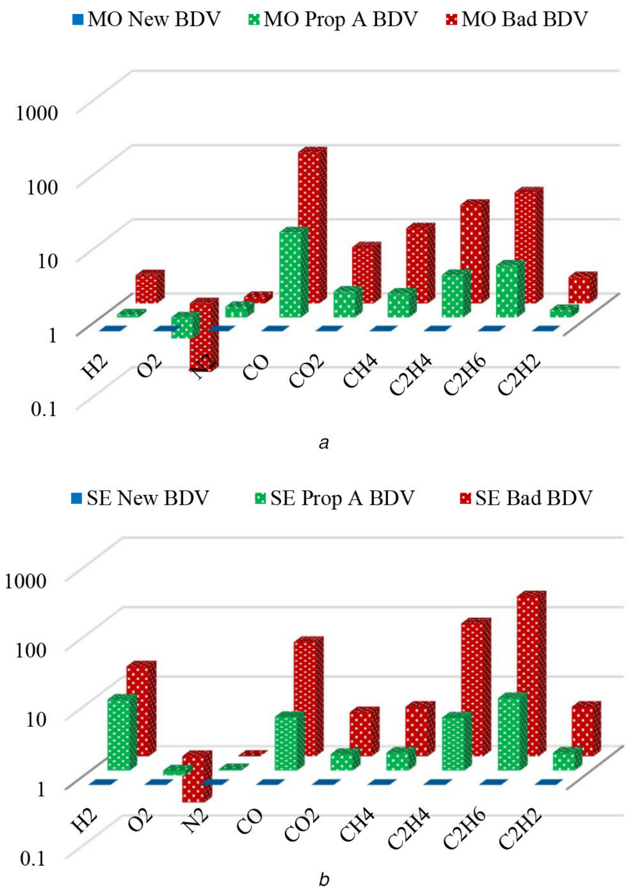

Fig. 8 *Change in the generation of dissolved gasses (p.u.) for SE at different ageing factors under high-energy discharge*
(a) For MO,
(b) For SEs

increased by 81 times, C_2H_2 increased 5 times, and H_2 increased 20 times.

Similarly, for MO, all the gases were increasing other than O_2 and N_2. CO increased 108 times from new oil to bad oil. While C_2H_6 increased 31 times, C_2H_4 increased 21 times. C_2H_2 increased 2 times and H_2 increased 2 times. It is to be mentioned that the reference for p.u. is based on the gas values for fresh oil.

The increases in CO and CO_2 are seen because of degradation witnessed by the number of cellulose particles present in the degraded oil. The increase in acetylene and hydrogen is attributed to the high-energy discharging activity. This continuous high arc leads to high ionisation energy within the oil and generates free radicles such as H• and CH•. These free radicles recombine with the time that lead to H_2 and C_2H_2 as shown below:

$$\mathrm{H}\cdot + \mathrm{H}\cdot \Rightarrow \mathrm{H_2}$$

$$\mathrm{CH}\cdot + \mathrm{CH}\cdot \Rightarrow \mathrm{C_2H_2}$$

Similarly, the formation of ethane and ethylene is due to the recombination of CH_3• and CH_2• free radicles, respectively.

These fault gasses are further evaluated using the Duval triangle and Duval pentagon methods. The Duval triangle uses three gases, CH_4, C_2H_4, and C_2H_2, to distinguish mainly between different types of electrical and thermal faults [25, 26]. The analysis of the fault gasses based on Duval's triangle and Duval's pentagon fault analysis are presented in Fig. 9.

The trending of the fault gas with ageing as per the Duval triangle and Duval pentagon is similar for both SE and MO. A clear shift is seen from the fresh oil to bad oil that goes from the D1 area (electrical discharge of low-intensity faults) to the D2 area (electrical discharge of high-intensity faults). It is explained by the increases of C_2H_4 in ratio compared with the decreases of C_2H_2 and CH_4. The C_2H_2 and C_2H_4 are used in analysis methods to represent high-energy faults and high-temperature faults [27]. Change in H_2 represents very low-energy faults like the initiation of partial discharges. CH_4 is also representative of such faults and is always formed in addition to H_2.

The Duval pentagon representation uses five hydrocarbon gases: H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2 [20]. Duval pentagon may be used alone, and it is not intended to replace the Duval triangle for oils; rather, it is to reveal complementary information. The results of Duval pentagon are in accordance with the Duval triangle for both MO and SE. Importantly, it is to be noticed that, for moderately aged oil, the fault classification is D2 from MO and it is in D1 for SEs [28]. This presents the phenomenal behaviour of ester fluids under electrical fault conditions.

4 Conclusion

The behaviour of MO and SEs at different ageing factors under high-energy discharge electric fault conditions is studied. The influence of such faults on oil degradation and gassing tendency with the oil ageing factor has been the subject of focus. Oil degradation is analysed by turbidity, the concentration of DDP, and particle count. The influence of high-energy discharge faults on oil degradation at different ageing factors is better in the case of SEs as compared to that of the MO. The gassing behaviour of MO and SE under high-energy discharge fault conditions is reported by Duval's triangle and pentagon methods for dissolved gas analysis. The behaviour of MO and SE with ageing under high-energy electrical fault conditions is almost similar. However, the intensity of fault classification is higher in MO than a SE. Also, the increase in combustible gasses in MO increased rapidly with ageing, whereas in SEs, the traces of combustible gasses are significant only at higher ages.

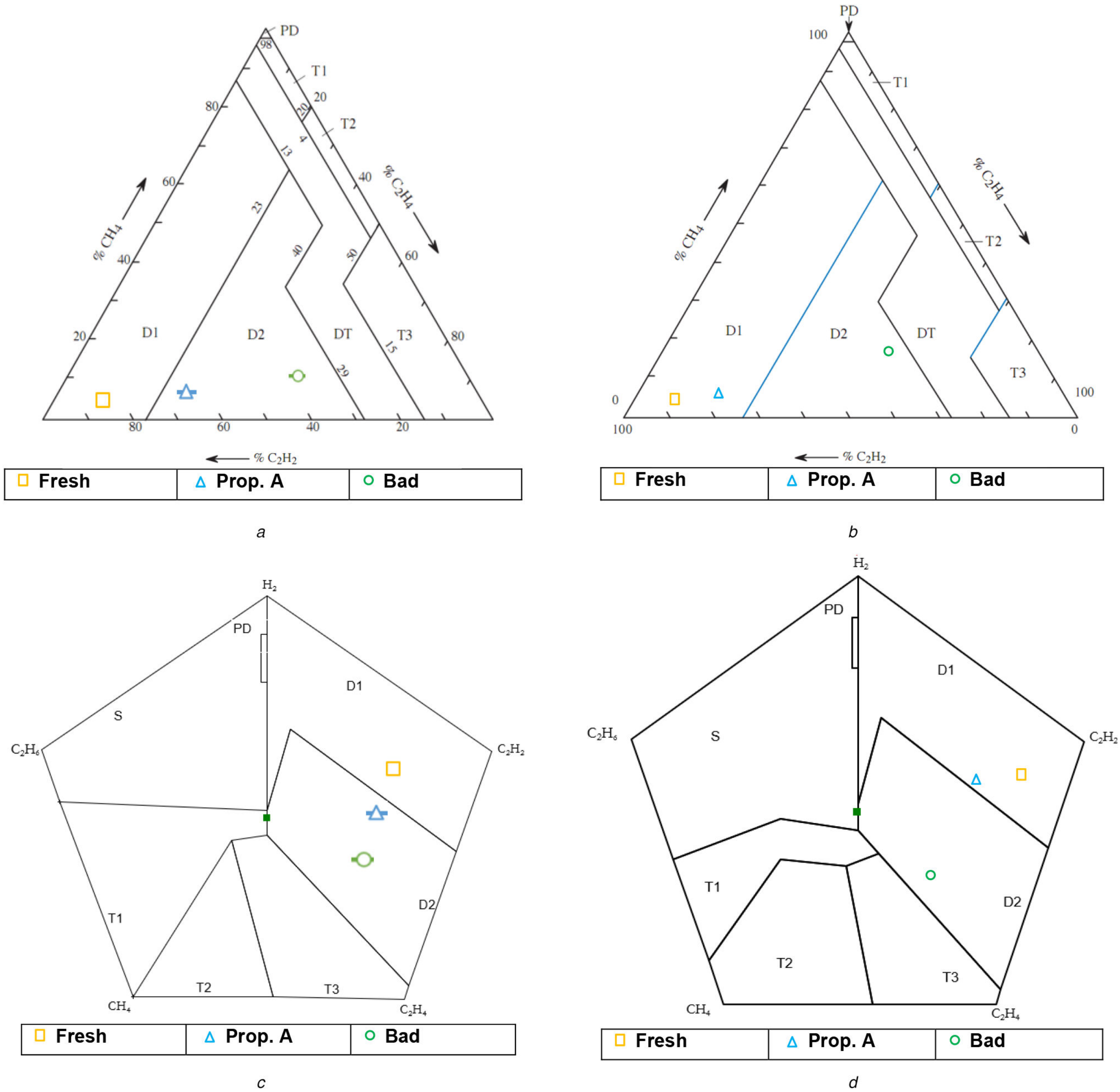

Fig. 9 *Representation of fault gasses in Duval's triangle and Duval's pentagon for oils at different ageing factors*
(a) Duval's triangle for MO,
(b) Duval's triangle for SEs,
(c) Duval's pentagon for MO,
(d) Duval's pentagon for SEs

5 References

[1] Fofana, I.: '50 years in the development of insulating liquids', *IEEE Electr. Insul. Mag.*, 2013, **29**, (5), pp. 13–25

[2] Beroual, A., Henry, B., Rudy, S., *et al.*: 'Comparative study of AC and DC breakdown voltages in Jatropha methyl ester oil, mineral oil, and their mixtures', *IEEE Trans. Dielectr. Electr. Insul.*, 2018, **25**, (5), pp. 1831–1836

[3] Piotrowski, T., Rozga, P., Kozak, R.: 'Comparative analysis of the results of diagnostic measurements with an internal inspection of oil-filled power transformers', *Energies*, 2019, **12**, p. 2155

[4] Mohan Rao, U., Fofana, I., Betie, A., *et al.*: 'Condition monitoring of in-service oil filled transformers: case studies and experience', *IEEE Electr. Insul. Mag.*, 2019, **35**, (6), pp. 33–42

[5] Mehta, A.K., Naresh, R., Chauhan, S.: 'Development of a novel dual temperature model for insulation aging in oil immersed transformers', *IEEE Trans. Dielectr. Electr. Insul.*, 2015, **22**, (5), pp. 2723–2736

[6] Li, Y., Zhong, L., Yu, Q., *et al.*: 'Influence of moisture content on cellulose structure and breakdown strength of vegetable oil-impregnated paper', *IEEE Trans. Dielectr. Electr. Insul.*, 2019, **26**, (4), pp. 1245–1252

[7] Fernandez, I., Ortiz, A., Delgado, F., *et al.*: 'Comparative evaluation of alternative fluids for power transformers', *Electr. Power Syst. Res.*, 2013, **98**, pp. 58–69

[8] Mohan Rao, U., Sood, Y. R., Jarial, R.K.: 'Ester dielectrics: current perspectives and future challenges', *IETE Tech. Rev.*, 2017, **34**, (4), pp. 448–459

[9] IEEE C57.104-2008, IEEE Standard: 'IEEE guide for the interpretation of gases generated in oil-immersed transformers', 2008

[10] Loiselle, L., Fofana, I., Sabau, J., *et al.*: 'Comparative studies of the stability of various fluids under electrical discharge and thermal stresses', *IEEE Trans. Dielect. Electr. Insul.*, 2015, **22**, (5), pp. 2491–2499

[11] Loiselle, L., Mohan Rao, U., Fofana, I.: 'Influence of aging on oil degradation and gassing tendency under electrical faults for mineral oil and synthetic ester under low energy discharges', *Energies*, 2020, **13**, (3), p. 595

[12] Wilhelm, H. M., Tulio, L., Jasinski, R., *et al.*: 'Aging markers for in-service natural ester-based insulating fluids', *IEEE Trans. Dielectr. Electr. Insul.*, 2011, **18**, (3), pp. 714–719

[13] Fox, N.J., Stachowiak, G.W.: 'Vegetable based lubricants – a review of oxidation', *Tribol. Int.*, 2007, **40**, pp. 1035–1046

[14] CIGRE Technical Brochure 761: 'Condition assessment of power transformers'. 2019, 158 pages

[15] Hadjadj, Y., Fofana, I., John, S., *et al.*: 'Assessing insulating oil degradation by means of turbidity and UV/Vis spectrophotometry measurements', *IEEE Trans. Dielect. Electr. Insul.*, 2015, **22**, (5), pp. 2653–2660

[16] Gray, I.A.R.: '*A guide to transformer oil analysis*' (Transformer Chemistry Service, 2009)

[17] Hamidi, H., Mohammadian, E., Rafati, R., *et al.*: 'A role of ultrasonic waves on oil viscosity changes in porous media'. IEEE Conf. on Clean Energy and Technology (CEAT), Lankgkawi, 2013, pp. 1–6
[18] Bakar, N., Abu-Siada, A., Islam, S.: 'A review of dissolved gas analysis measurement and interpretation techniques', *IEEE Electr. Insul. Mag.*, 2014, **30**, (3), pp. 39–49
[19] ASTM D 877–13: 'Standard test method for dielectric breakdown voltage of insulating liquids using disk electrodes', 2013
[20] Mladenov, E.S., Staykov, G., Cholakov, G.: 'Water saturation limit of transformer oils', *IEEE Electr. Insul. Mag.*, 2009, **25**, (1), pp. 23–30
[21] Fofana, I., Borsi, H., Gockenbach, E.: 'Fundamental investigations on some transformers liquids under various outdoor conditions', *IEEE Trans. Dielectr. Electr. Insul.*, 2001, **8**, (6), pp. 1040–1047
[22] Krins, M., Reuter, M., Borsi, H., *et al.*: 'Breakdown and flashover phenomena related to the presence of high absolute water contents in clean and carbonized transformer oil'. Annual Report Conf. on Electrical Insulation and Dielectric Phenomena, Quintana Roo, Mexico, 2002
[23] CIGRE Working Group 12.17: 'Effect of particles on transformer dielectric strength'. Technical brochure 157, 2000o, 44 pages
[24] Beite, A., Mohan Rao, U., Fofana, I., *et al.*: 'Influence of cellulose paper on gassing tendency of transformer oil under electrical discharge', *IEEE Trans. Dielect. Electr. Insul.*, 2019, **26**, (6), pp. 1729–1737
[25] CIGRE Working Group: '*Guide for transformer maintenance, A2.34*' (2011)
[26] Duval, M., Lamarre, L.: 'The duval pentagon-a new complementary tool for the interpretation of dissolved gas analysis in transformers', *IEEE Electr. Insul. Mag.*, 2014, **30**, (6), pp. 9–12
[27] Duval, M.: 'The duval triangle for load tap changers, non-mineral oils and low temperature faults in transformers', *IEEE Electr. Insul. Mag.*, 2008, **24**, (6), pp. 22–29
[28] Duval, M., Lamarre, L.: 'The new duval pentagons available for dga diagnosis in transformers filled with mineral and ester oils'. Electrical Insulation Conf. (EIC), USA, 2017, pp. 279–281