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Predictive maintenance of railway transformer oil based on periodic content analysis

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KEYWORDS

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Dielectric
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ABSTRACT

The high frequency of operation of commuter trains, due to passenger demand as well as the selection of railway as the mode of daily transportation for commuting on weekdays, increases the usage of on-board power, especially for a train's traction system. As maintenance is rarely performed on transformer oil, it deteriorates and negatively affects transformer performance, increases heat, and may damage the transformer as well. This will result in significantly costly maintenance expenses for train operators. Therefore, this paper proposes a predictive maintenance schedule for transformer oil. The recommendations are based upon an analysis of transformer oil contents and its properties over a 90-month period of operation. A linear correlation between the properties of the oil and the train's period of operation yielded a predictive maintenance schedule, primarily reclamation and filtration, for the oil at the threshold of each property. Major oil changes are to be considered when all properties are approaching their thresholds. As oil deterioration increases over time, a specific maintenance schedule was suggested. This was tested and observed on several transformer units. The content analysis of each oil is also discussed. Based on the results, this predictive maintenance schedule can be used on other trains with the same transformer model or other trains using the same type of insulating oil.

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1.0 INTRODUCTION

A commuter train is a passenger rail transport service that primarily operates between city centres. Many people choose commuter trains for their daily commute to work on weekdays. These numbers are on the rise as it helps commuters not only avoid heavy traffic and shorten travel times but eliminates the cost of fuel and vehicle maintenance. Therefore, in order to meet rising demands, train operators will have to eventually increase the frequency of train operations which will result in heavy usage of the on-board power supply which draws power from a high-voltage transformer. Train operators already have a periodic maintenance schedule as well as methods to solve issues that arise (Feng et al., 2017a; Kiessling et al., 2018; Zhou et al., 2017; Munteanu et al., 2017; Lu and Liu, 2016; MehdipourPicha et al., 2019; Feng et al., 2017b; Rao et al., 2019; Saponara et al., 2016; Chamaret and Frugier, 2016; André-Philippe et al., 2016 and Noman et al., 2019). However, oil-insulated high-voltage transformers (Adekoya & Adejumobi, 2017; Maharana et al., 2018a; Maharana et al., 2018b; Evangelista et al., 2017; Emara et al., 2017; Garcia et al., 2020) only undergo maintenance and testing once every six months (Saponara et al., 2016; Rao et al., 2019; Noman et al., 2019) even though it is a critical component of a train's operation (Feng et al., 2017b; Chamaret et al., 2016). Therefore, the failure of a transformer due to deterioration, aging, and oil degradation is not only unacceptable but could prove catastrophic (Fofona et al., 2016; Tee et al., 2016; Regnima et al., 2018; Sitinjak et al., 2003; Hill et al., 1996; Azli et al., 2013).

In the best-case scenario, the train simply breaks down in the middle of the track with no injuries or casualties. In the worst-case scenario, the transformer oil overheats and the transformer catches fire putting the lives of the passengers in danger. In both scenarios, the responsibility and blame will fall squarely on the operator. Therefore, as transformer oils can last for up to 30 years (Adekoya & Adejumobi, 2017; Wibowo et al., 2011; Ayuningsih et al., 2017; Fu et al., 2009), regular oil testing is necessary to determine its electrical properties, its expiry date, if regeneration or filtration is required, to reduce oil costs, to increase the product life cycle of the transformer's components, to prevent premature transformer failures, and to optimise safety (Amalanathan et al., 2019; Kaur and Singh, 2016; Baruah et al., 2019; Munajad and Subroto, 2018; Betie et al., 2019, Ranga et al., 2018; Fofana et al, 2016; Gao et al., 2016; Shaban et al., 2016; Adekoya and Adejumobi, 2017; Wibowo et al., 2011; Ayuningsih et al., 2017 and Fu et al., 2009).

The main function of transformer oil is to insulate the transformer from arc discharge and to cool its coil and core. This is performed by measuring the properties and contents of the oil, particularly its dielectric property. Dielectric materials or substances are very poor conductors of electric current. The higher the dielectric value, the higher the amount of electrical energy that it can store, therefore, the better the electrical resistance and insulation (Mansour et al., 2016; Lv et al., 2017; Dong et al., 2017; Aberoumand and Jafarimoghaddam, 2018; Rafiq et al., 2019; Rao et al., 2018; Hamid et al., 2016; Nazari et al., 2016, Rao et al., 2016 and Darma, 2008). The dielectric value of transformer oil is called the breakdown voltage (BDV). BDV is determined by evaluating at what voltage sparking threads when separated at a particular distance between two electrodes immersed in oil. A low BDV value indicates the presence of moisture, impurities, and other conductive substances in the oil while a higher BDV value indicates a dry and clean oil. As such, BDV is an important and common transformer oil test as it is the primary indicator of oil health and can be done easily at the site. 30 kV is considered the minimum BDV value; or dielectric transformer oil strength; at which an oil can safely be used in a transformer (Wibowo et al., 2011; Ayuningsih et al., 2017; Fu et al., 2009).

Over the years, the materials insulating the inside of the transformer and its electrical equipment break down and release gases inside the device. The distribution of these gases may be caused by a type of electrical fault while the rate of gas production may indicate the intensity of the fault. In any good preventive maintenance programme, identifying the gases being produced by a given unit can be very useful information (Feng et al., 2017a). Dissolved gas analysis (DGA) can be used to determine the amount of dissolved gases (Cui et al., 2019; Chen et al., 2019; Gui et al., 2020; Zhou at at., 2020; Ma et al., 2019; Dai et al., 2017; Bustamante et al., 2019; Park et al., 2019; Uddin et al., Liang et al., 2018; Fan et al., 2019; Taha et al., 2017; Fan et al., 2018; Bakar and Abu-Siada, 2017; Faiz and Soleimani, 2017; Falafah and Yehia El-Naggar, 2018). This entails sampling the oil and sending it to an analytical laboratory. Remote DGA units can also be transported and used on-site while others can be connected directly to a transformer. Although many types of gases are produced when gassing occurs in a transformer, an analysis of nine key gases; nitrogen, oxygen, carbon monoxide, carbon dioxide, acetylene, ethylene, methane, ethane and hydrogen; produced during the process is enough to provide adequate information such that the additional gases are not generally investigated. Oil samples, laden with these gases, are pumped into a gas chromatography machine where the columns isolate the gases. The columns selectively retard the sampled gases and they are marked as flowing at different chromatograms; or times; past a detector. Separate gases are then detected as ambient gases by a thermal conductivity detector while a flame ionization detector detects hydrocarbons and carbon oxides. When in very low concentrations, a methanator is used to detect carbon oxides by converting them to methane. However, as a diagnostic method, DGA has many drawbacks, one of which is that it cannot precisely locate a fault. If a transformer is refilled with fresh oil, a DGA will not be able to indicate faults. In the presence of electrical and thermal issues, a fundamental gas; hydrogen; emerges and contributes to the deterioration of cellulose and oil thereby playing a major role in the early identification of failure modes or irregular conditions within the transformer (Gouda et al., 2019; Zhang et al., 2018; Hengyi and Youyuan, 2010 and Prasojo et al., 2017).

A transformer's faults due to a DGA are thermal faults, overheating winding, overheating oil, corona (Swati et al., 2018), and arcing. Thermal failures are indicated by the existence of strong isolating decomposition by-products. As solid insulation is typically made of cellulose fibre, it normally breaks down, but the rate of deterioration increases as the isolation temperature rises. When an electrical failure occurs, it releases energy that breaks the insulating fluid's chemical bonds. If these elements are broken, these bonds stabilise the fault gases easily. For each of these gases, the energies and rates at which they are produced vary. This enables the analysis of gas data to assess the type of faulting operation taking place inside the electrical equipment. Overheating windings usually allow the cellulose isolation to decompose thermally. DGA findings indicate high concentrations carbon oxides; monoxide and dioxide; with methane and ethylene observed at higher concentrations in extreme cases. Overheating oil results in liquid breakdown, as well as the formation of methane, ethane, and ethylene. Corona is a partial discharge with DGA indicating elevated hydrogen levels. Arcing is the most extreme state that a transformer can be in and is detectable even at low acetylene levels. Interpretation of the results obtained from a transformer requires awareness of the unit era, the loading period, as well as the date of significant maintenance activities; such as oil filtering. The IEC Standard 60599 and the ANSI IEEE Standard C57.104 provide instructions for determining the condition of an equipment based on the amount of gasses present and the volume ratios of gas pairs. The first step in assessing DGA findings is to evaluate the concentration levels (in ppm) of each main gas in the samples. Values are measured over time for each of the main gases so the rate of change of the different gas concentrations can be calculated. Any sharp rise in key gas concentrations is indicative of a possible transformer crisis.

Another method of transformer oil analysis is water content; which is limited to below 30 to 35 ppm of water in transformer oil as water affects the dielectric properties of the insulation and the aging rate of the insulation materials (Yang et al., 2019; Taylor, 2004; Mahanta and Laskar, 2017; Yusoff et al., 2018 and Sarfi et al., 2017). It is, therefore, vital that transformer oils to have low water content for safe operation, reliability, and to slow the aging of the transformer (Karthikeyan et al., 2019; Dahim et al., 2018; Palitó et al., 2018 and Dhofir et al., 2018). In extreme cases, the insulation of a transformer can fail due to excess water. Humidity and water content in transformer oil are strongly discouraged as they adversely affect the oil's dielectric properties (Du et al., 2001; Perkasa et al., 2014). It also impacts the transformer’s core paper insulation and winding. As paper is extremely hygroscopic, it will absorb the maximum quantity of oil and water which will affect it insulation capabilities and decrease its life cycle. However, as oil becomes hotter in a charged transformer, the water solubility of the oil also increases. As a result, the insulation paper releases water into the transformer oil and raises its water content. Therefore, the temperature of the oil is critical when collecting a sample for testing. Acids are also formed in the oil during oxidation (Raof et al., 2019). As acids also increase the water solubility of oil, oils containing higher concentrations of acid and water deplete at a faster rate. Water content in oil should be measured in ppm (parts per million unit). As recommended by IS–335 (1993), oils are permitted to only have a water content of up to 50 ppm. However, in order to detect such low concentrations of water, more precise and sophisticated water content calculation instruments are required; such as the Coulometric Karl Fisher Titrator.

Transformers account for nearly 60% of the cost of high-voltage substations (Feng et al., 2017b) while some require more than a year to repair (Feng et al., 2017b). Therefore, given the long downtime for repairs, it is imperative to accurately monitor the health of the transformer. Over time, as the transformer’s insulator oil degrades due to mechanical, electrical, and chemical stresses, its quality is an excellent indicator of its condition (Tee et al., 2016). For years, measuring the interfacial tension (IFT) between the transformer oil and water, in accordance with the ASTM D971 standard, was used to effectively monitor oil and transformer health. At the interface formed between two the immiscible liquids, the molecular cohesive and adhesive forces cause a “film” to form which is analogous to an elastic sheet with an associated tension force. This is called interfacial tension (IFT) and it is very sensitive to impurities in either liquid. In fact, IFT measurements are an excellent way to test the quality of many other commercially used liquids; such as jet fuel (Taylor, 2004). Therefore, it is useful in assessing the existence of polar pollutants and products of oil decay. Good new oil typically exhibits high tension between both surfaces. However, as transformer oil degrades over time or as contaminants are introduced, the IFT between it and the pure water will reduce indicating the deteriorating health of the transformer (Yang et al., 2019). Contaminants from oil oxidation also lower the IFT. The way to calculate the attractive molecular force between water and oil in Dyne/cm or milli-Newton/meter is the IFT between the interface of the water and the oil.

Acidic transformer oil is a deleterious commodity. When an oil becomes acidic, it becomes more soluble in the water content of the oil. Acidic oil also diminishes the insulating properties of winding paper insulation (Chen et al., 2019; Adekoya & Adejumobi, 2017). As acidity hastens the process of oxidation in the oil, in the presence of moisture, it also causes iron to rust. Transformer oil acidity tests may be used to calculate contaminant acid constituents. The acidity is expressed in mg of KOH; where the acidity of oil needed to neutralise the acid present in a gram of oil or the number of neutralisations. A transformer's insulating oil only passes an acidity test if the acidity content does not exceed 0.2 mg of KOH/g oil as per the recommendations of the American Society of Testing Materials (ASTM) Test Method. This is the critical acid number and, if this amount is surpassed, the degradation increases quickly.

In this paper, the transformer oil of the commuter rail system connecting Kuala Lumpur International Airport to Kuala Lumpur Central was studied. It comprises of two types of commuter trains (Figure 1); namely, express commuter rails (ECR) and transit commuter rails (TCR) and covers a distance of 59 kilometres (Figure 2) (Abdullah et al., 2014; Abdullah et al., 2018). During its previous maintenance session, the primary and secondary dampers were replaced in order to reduce body vibrations. Due to curved tracks, dynamic vibrations and swaying are observed during operation (Abdullah et al., 2018). The slowing down of a commuter train is observed by the reduction in its longitudinal acceleration (Abdullah et al., 2014). The trend and performance of its brake system were also analysed and studied (Habeeb et al., 2020). The data of the transformer oil was taken within 90 months of operation. Within this period, the transformer oil was not replaced. Predictive maintenance of the oil; such as filtration and oil reclamation; were performed when certain parameters met their limits. Based on the trend of the readings and correlations between variables and time, predictive maintenance can be performed or omitted based on these results.

Figure 1: Commuter train.

Figure 2: Commuter track route (Abdullah et al., 2014; Abdullah et al., 2018).

2.0 METHODOLOGY

The transformer used in this research is used by the Siemen Desiro ET 425 train model. Figure 3 pictures the traction transformer by Siemens for Electric Multiple Units (EMU) (Siemens, 2020). Figure 4 shows the inside tank where the transformer is installed. The transformer is liquid cool using SHELL Diala Oil B mineral oil. This high-performance, non-inhibited insulating oil; which meets the specifications for DIN 57370-1/VDE 0370 Part 1, Class A and IEC 296, Class II for high voltage 25 kV application; is filled in the tank. The transformer unit is forced cooled by this oil via a three-phase motor pump. In order to lower the temperature of the oil, an air-oil heat exchanger is used. The system is open to ambient and protected by a silica gel breather which keeps the oil dry between maintenance cycles. The breather is mounted and completely protected against damages from flying stones by metal screens. An additional storage box (similar to a conservator) is positioned between the breather and the vessel to keep the oil in the vessel. Two coolers are installed in the cooling compartment and are easily exchangeable and dismountable from the mechanical rig. Each and every cooler is connected to a radial ventilator that provides sufficient airflow to dissipate the high temperatures. For oil circulation, a pump is installed. The pump sucks the oil from the vessel and pumps it into the heat exchanger where it flows through pipes and tubes directly into the coil system which works as a heat exchanger. The main transformer is a single-phase transformer with traction windings, to feed the four-quadrant chopper, as well as an auxiliary winding. The consumers connected to the outputs are switched on and off without influence from the transformer. The main transformer transforms the primary voltage from the 25 kV 50Hz -line to 1st output 1180V AC, 50 Hz to supply traction and 2nd output 350 V AC, 50 Hz to supply auxiliary devices. Table 1 shows the transformer system's properties.

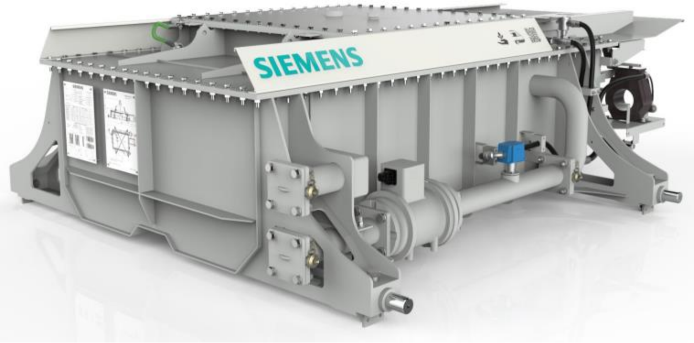


Figure 3: The train's transformer.

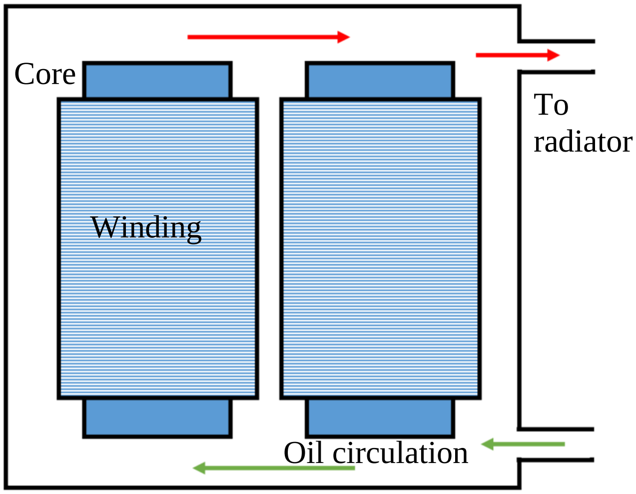


Figure 4: The fixed main transformer in the tank.

Table 2 tabulates the preventive maintenance schedule based on the operation mileage. A dielectric strength test and a moisture content test were scheduled at T4. The definitions of the terms are as follows; T3 = 3 times T2, T4 = 5 times T3, T5 = 5 times T4, and T6 = 2 times T5.

The penetration of the oil into the coil, even under lowest temperatures, is essential and facilitated through the existence of layers and ducts within the coil. The transformer oil of choice; the SHELL Diala B; fulfils the required cooling capabilities across a full temperature scale (Wibowo et al., 2011; Ayuningsih et al., 2017; Fu et al., 2009). The filling level was calculated at 20°C. The oil expansion factor α was set at 76 x 10^{-5} K^{-1}. The oil compensation levels for the oil at each temperature is presented in Table 3. This was largely dependent upon the ambient temperature. If the ambient temperature was below 20° C, the quantity of oil was reduced. If the ambient temperature was above 20° C, then the quantity of oil was increased.

Table 1: Properties of the transformer system.

Electrical Data, Single Phase Transformer	
Rated Voltage	25 kV
Max.-Operating Voltage	27.5 kV
Max.- Voltage	30 kV (5 min.)
Min.- Operating Voltage with full load	23,0 kV 50 Hz - Traction 20,0 kV 50 Hz - Auxiliary
No Load Losses at 22,5 kV	550 W
Primary	
Rated Power	1030 kVA
Rated Current	41,1 A
Rated Voltage	25 kV
Resistance (20°C)	7,9 Ω
Load osses (only sinus Current)	43,4 kW at 41,1 A
Test Voltage	60 kV / 50 Hz / 1 min.
Traction	
Rated Power	2x 410 kVA
Rated Current	2 x 348 A
Rated Voltage	1180 V
Resistance (20°C)	37 mΩ
leakage inductance	2.56 mH
u_x (referred at 450 kVA)	23.7 %
Test Voltage	3.5 kV / 50 Hz / 1 min.

Table 2: Preventive maintenance schedule.

Maintenance Term	Operating Time	Timing term
T2	10 000 km +10%	10 days
T3	30 000 km +10%	1 month
T4	150 000 km +10%	6 months
T5	750 000 km +10%	2 years
T6	1.500.000 km +10%	4 years

Mineral oils; such as the SHELL Diala B; with their specified identities are defined as oils mainly used to create high insulation levels in electrical appliances (Wibowo et al., 2011; Ayuningsih et al., 2017; Fu et al., 2009). SHELL Diala B has high ageing stability, excellent dielectric abilities, and good thermal characteristics. It fulfils all the requirements of the German Standard VDE 0370/ DIN 57370 part 1 and international standards according to the IEC 296. It is specially refined without the addition of mineral strange ageing materials. All SHELL Diala oils are not to be mixed with other cooling liquids; such as PCB, silicon oil, or ester. With adequate maintenance, the oil has a life cycle of 30 years. All materials used in the transformer unit are of organic origin and subject to ageing from exposure to oxygen, heat, moisture, humidity, and other chemical interferences that cause catalytic processes.

Table 3: The oil compensation levels.

Temperature	Compensation (liter)	Quantity of oil (kg)	Volume at 20° C (liter)
10° C	-6	680-710	750-790
12° C	-5		
14° C	-4		
16° C	-2		
18° C	-1		
20° C	0		
22° C	+1		
24° C	+2		
26° C	+4		
28° C	+5		
30° C	+6		
32° C	+7		
34° C	+8		
36° C	+9		
38° C	+11		
40° C	+12		

Transformer oil needs to be put through a filtration process to treat and purify it (Gainullina & Tutubalina, 2020; Chen, 2020; Salvi & Paranjape 2017; Wang et al., 2018; Jun Gong et al., 2017; Gong et al., 2017a, Gong et al., 2017b; Safiddine et al., 2017; Guerbas et al., 2016; Guerbas et al., 2017; Guerbas et al., 2018; Hafez et al., 2017; Ab Ghani et al., 2018; Allaf & Mirzaei, 2017; Ab Ghani et al., 2018). Filtration of the insulating oil extracts sludge and moisture from the transformer oil. The advantages of oil filtration are: improved oil insulation properties, longer transformer life span, decreased breakdown of the transformer, and good investment returns for a better engine. Another maintenance strategy to improve the quality of used transformer oil is oil reconditioning (Rodiah & Haryono, 2018; Rodiah et al., 2020). Oil reconditioning reclaims the oil and extends its life for reuse. The steps in oil reclamation include: increment of oil temperature, elimination of dirt and impurities, filtration via candles filter, centrifugal motion filtration, as well as dehydration and degasify of the extracted oil. The temperature of the oil is increased to 65°C to provide latent heat to separate moisture and gases. It also makes it easier to filter the oil due to decreased viscosity. There are two methods with which to remove sludge, debris, and soil from transformer oil. A classical edge filter or depth style filter may be used to filter the insulating oil via filter candles. However, new developments have been made in which transformer oil filtration machines use filter cartridges instead. Another way to separate dirt from oil is through centrifugation which eliminates the ongoing cost of replacing filters. The insulating oil is then dehumidified and degassed in a chamber in the dehydration stage. As research indicates that contaminated oil causes 80 per cent of all oil-related failures and breakdowns (Jaber et al., 2016), preventive maintenance is, therefore, essential in ensuring the optimal reliability of the machinery. As such, using reliable transformer oil filtration equipment can achieve an effective insulating oil filtration which will improve the transformer's performance and reliability. The limits of the analyses are shown in Table 4. These limits are based on the manual and manufacturers guide for the maintenance of the transformer.

Table 4: Oil analyses and their limits.

Analysis	**Limit**
Water content (WC), ppm	50 maximum
Interfacial tension (IFT), mN/m	20 minimum
Dielectric strength (DS), kV	30 minimum
Carbon dioxide (CO_2), ppm, µl/l	2500 maximum

3.0 RESULTS AND DISCUSSION

Tables 5 to 8 tabulate the transformer oil analyses results for ECR 1 to 10 and TCR 1 to 10. The data was collected once every six months or T4. Of the actual oil analyses data, only four results are considered critical: water content, IFT, DGA carbon dioxide (CO_2), and dielectric strength. The deterioration of transformer oil is determined by increments in water content and carbon dioxide and reduction of IFT and dielectric strength. Graphs of these analyses are shown in Figures 5 to 12 for ECR and TCR. Water content and CO_2 generally showed increasing trends for both ECR and TCR as the operation period increased while IFT and dielectric strength showed increasing trends. Further analysis was performed by developing a linear correlation between the data and time which produced the rate per unit of time. For water content, the rate was measured as ppm/month, for IFT mN/m/month, for CO_2 ppm/month, and for dielectric strength kV/month. From this analysis, the higher the absolute value of the rate, the higher the rate of transformer oil deterioration. Tables 9 and 10 present the analyses of the rate for both ECR and TCR, respectively. The average rate represents the final value of the rate.

As seen in the tables, the average rate of water content per month was almost identical for both TCR and ECR with 0.1332 and 0.1310 ppm/month, respectively. This suggested that, for both types of trains, differences in loads and operation routines did not affect the rate of water content increments in their transformer oils. However, ECR had higher rates of IFT, CO_2, and dielectric strength than TCR. The absolute value rate of IFT was 0.2005 mN/m/month for ECR but only 0.1957 mN/m/month for TCR. The rate of CO_2 was 6.5424 ppm/month for ECR and 4.9737 ppm/month for TCR while the rate of dielectric strength for both ECR and TCR were 0.1848 kV/month and 0.1434 kV/month, respectively. This could be due to differences in the standard operation routines and loads of ECRs and TCRs. For instance, ECR is physically weightier than TCR and, therefore, requires more current to run its traction motor than TCR. The air-conditioning in ECRs are also maintained at comfort levels; which requires higher current and electric loads; as it serves international passengers. This continuous use of higher currents and heavier electrical loads rely fully on the transformer; which will significantly affect the transformer oil. In comparison, TCR is lighter and, therefore, requires less current.

These three results were found to simultaneously increase as the operation time increased. As the preventive maintenance schedule of transformer oil, for filtration, is based on a reduction in dielectric strength, the transformer oil of ECRs required earlier maintenance the transformer oil of TCR. During the 90-month operational period, whenever the dielectric strength decreased to bare minimum levels; 30 kV; preventive maintenance via oil filtration was performed. However, although filtration improves dielectric strength, it is not able to renew it to its dielectric strength when it was fresh and in brand-new condition. Over the time, the dielectric strength decreases again. It was discovered that whenever preventive maintenance through oil filtration was performed, the other three parameters; water content, IFT and CO_2; also improved.

Table 5: Transformer oil analysis for ECR 1 to 5.

	Maintenance Term, Month														
	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90
Analysis								**ECR 1**							
WC	28	19	27	23	25	23	25	31	25	40	37	33	37	39	35
IFT	34.42	33.39	32.54	35.47	35.23	34.66	28.26	23.35	24.15	22.75	22.64	20.17	22.78	23.75	20.24
DS	60	55	53	54	50	40	39	37	45	34	37	35	46	32	33
CO_2	274	144	1117	837	1015	1008	868	631	732	1056	1050	1042	1010	1044	1,100
								ECR 2							
WC	32	34	34	24	30	30	34	21	14	28	28	15	27	27	32
IFT	35.6	33.01	34.7	33.4	33.63	35.34	28.62	22.92	22.6	21.5	21.09	21.99	21.04	21.51	22.15
DS	53	60	56	53	41	34	34	52	60	49	51	52	46	39	34
CO_2	345	249	899	785	1257	865	757	286	606	721	993	1198	1094	1432	1007
								ECR 3							
WC	21	17	25	40	25	25	28	27	37	31	30	26	27	31	33
IFT	34.29	31.65	33.05	35.87	34.52	34.82	28.05	20.74	18.26	17.7	19.03	21.73	20.59	21.33	18.11
DS	55	60	59	55	49	36	54	37	42	37	38	45	38	50	44
CO_2	324	154	882	1,026	1069	1151	1024	382	684	880	834	944	972	760	773
								ECR 4							
WC	22	25	13	27	26	24	22	33	32	31	32	29	30	30	33
IFT	36.02	33.84	32.81	34.38	35.47	35.77	28.99	20.71	24.47	21.85	22.53	24.57	24.51	22.71	23.61
DS	42	57	53	46	55	53	54	55	45	42	47	38	42	50	26
CO_2	696	242	1580	1,106	1003	1428	996	947	1096	1230	1225	1438	1049	1021	931
								ECR 5							
WC	19	30	31	23	35	34	30	42	38	34	19	34	32	26	28
IFT	33.91	31.38	35.08	34.87	34.7	35.71	27.68	22.99	23.45	24.83	24	23.81	23.4	21.04	21.25
DS	60	56	46	59	40	42	41	25	26	46	50	36	32	52	30
CO_2	295	114	728	523	1107	1208	856	997	847	1028	983	1148	998	1188	1097

Table 6: Transformer oil analysis for ECR 6 to 10.

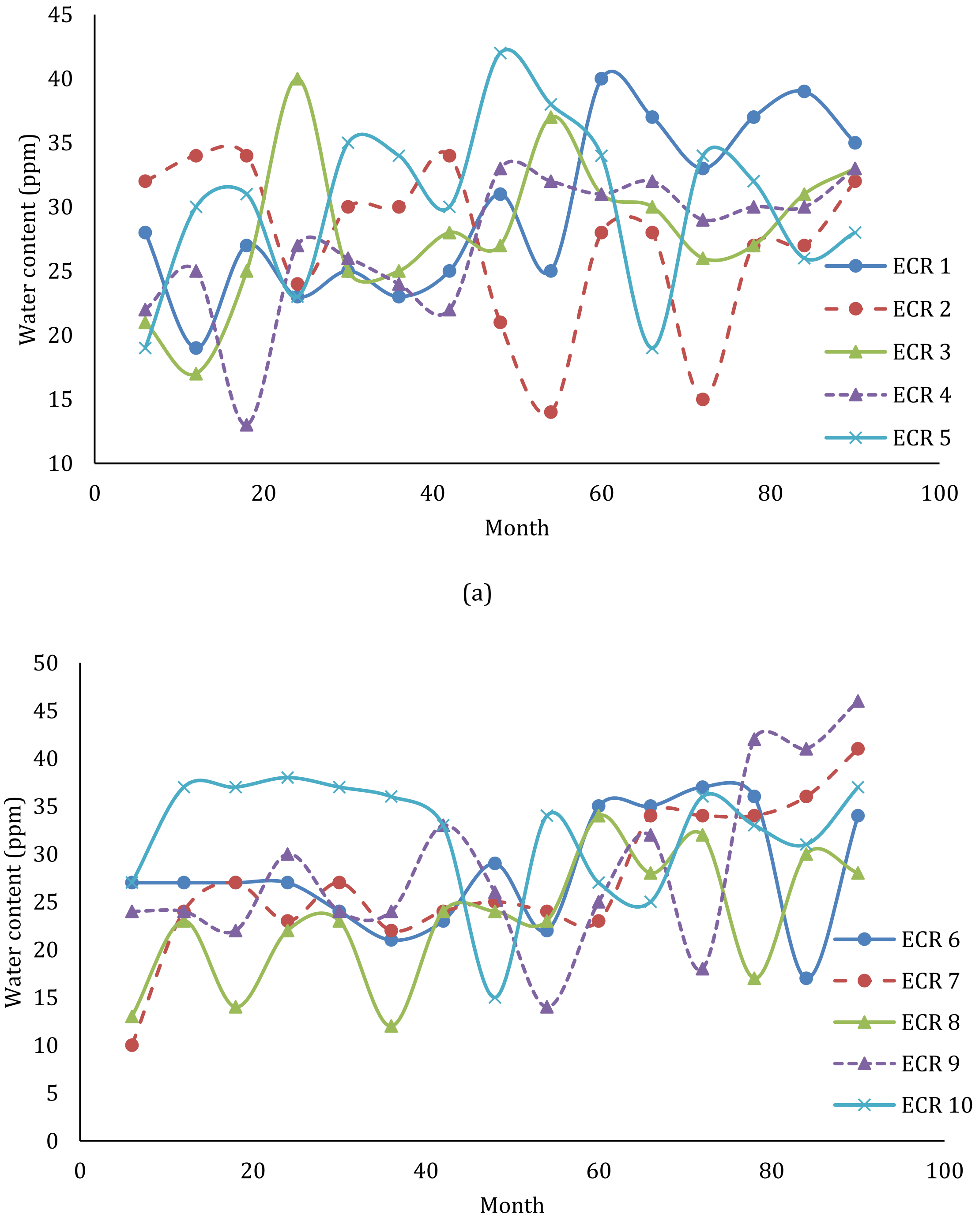
	Maintenance Term, Month														
	6	**12**	**18**	**24**	**30**	**36**	**42**	**48**	**54**	**60**	**66**	**72**	**78**	**84**	**90**
Analysis								**ECR 6**							
WC	27	27	27	27	24	21	23	29	22	35	35	37	36	17	34
IFT	33.64	33.31	33.39	34.95	35.23	35.25	28.14	18.6	18.94	18.49	20.12	19.91	21.16	20.72	19.62
DS	48	56	56	45	54	54	44	41	46	58	37	38	34	41.2	35
CO2	1387	1018	1566	1190	695	232	378	532	520	690	931	1210	908	1100	1,100
								ECR 7							
WC	10	24	27	23	27	22	24	25	24	23	34	34	34	36	41
IFT	34.97	34.07	33.84	36.43	34.58	35.72	26.74	24.02	22.77	22.74	21.03	20.01	20.3	20.92	20.75
DS	55	47	53	55	50	49	51	47	53	42	50	52	53	35	30
CO2	274	1701	1,368	2013	1512	759	315	519	786	1128	981	1041	1051	848	1007
								ECR 8							
WC	13	23	14	22	23	12	24	24	23	34	28	32	17	30	28
IFT	35.98	34.26	34.57	34.46	35.43	35.46	28.85	25.09	24.03	23.45	23.78	24.37	23.77	23.21	22.8
DS	60	50	55	56	47	53	56	34	44	37	37	41	56	52	42
CO2	201	1202	913	895	1108	1347	229	432	518	572	901	899	1097	896	773
								ECR 9							
WC	24	24	22	30	24	24	33	26	14	25	32	18	42	41	46
IFT	34.85	33.64	33.97	36.82	33.96	35.47	29.08	20.26	19.82	20.59	19.46	20.47	20.95	21.99	22.52
DS	41	60	55	43	48	38	42	37	54	43	51	55	43	29	24
CO2	132	1205	836	1034	851	736	260	576	628	634	1094	827	987	772	950
								ECR 10							
WC	27	37	37	38	37	36	33	15	34	27	25	36	33	31	37
IFT	35.94	33.54	34.58	35.58	35.08	35.97	27.29	32.7	28.62	28.13	26.73	27.62	25.52	25.39	26.18
DS	60	44	42	38	48	46	39	78	30	32	38	30	46	46	35
CO2	93	744	541	618	726	836	212	307	1350	874	704	1114	2288	2674	1097

Table 7: Transformer oil analysis for TCR 1 to 5.

	Maintenance Term, Month														
	6	**12**	**18**	**24**	**30**	**36**	**42**	**48**	**54**	**60**	**66**	**72**	**78**	**84**	**90**
Analysis								**TCR 1**							
WC	24	24	24	27	24	22	30	23	21	23	33	29	32	30	29
IFT	35.84	31.59	33.48	32.32	34.57	35.75	28.25	20.83	20.86	20.04	19.69	20.01	20.92	20.71	20.1
DS	60	57	60	55	53	50	54	54	57	60	57	40	43	41	34
CO_2	226	214	1104	1000	1068	1241	796	341	672	759	952	1246	1021	1232	980
								TCR 2							
WC	22	25	24	47	25	27	33	34	34	30	30	34	34	34	22
IFT	34.52	33.21	34.02	33	34.75	35.28	27.34	26.74	27.43	26.49	26	25.41	23.78	24.5	25.25
DS	60	58	47	50	50	51	52	33	31	31	40	40	40	35	45
CO_2	248	202	970	718	1044	776	609	309	396	495	674	725	762	908	716
								TCR 3							
WC	22	30	28	34	27	26	24	21	14	29	30	26	31	33	36
IFT	34.25	32.44	34.23	35.6	34.6	35.73	28.45	19.84	21.07	20.71	21.26	19.34	21.27	20.43	18.67
DS	49	46	49	44	41	45	44	49	41	41	42	36	43	32	35
CO_2	270	108	974	808	1075	1189	996	509	579	735	811	861	895	534	663
								TCR 4							
WC	11	25	27	25	27	22	25	27	19	24	33	33	31	29	32
IFT	34.1	33.5	34.44	34	34.81	34.59	28.11	20.93	21.51	19.58	20.1	19.23	19.88	20.34	19.51
DS	60	37	49	52	46	43	45	34	47	38	36	37	52	40	36
CO_2	312	166	905	745	1171	878	894	236	414	679	943	961	1028	1292	959
								TCR 5							
WC	13	24	14	24	23	10	21	23	24	27	28	31	31	31	33
IFT	35.68	34.64	35.71	36.81	35.45	35.99	27.32	24.27	23.34	22.98	24.35	24.35	22.51	24.05	22.14
DS	60	54	60	50	39	49	55	39	44	43	57	51	51	39	35
CO_2	47	206	1226	980	1094	1244	877	329	614	463	492	758	909	892	881

Table 8: Transformer oil analysis for TCR 6 to 10.

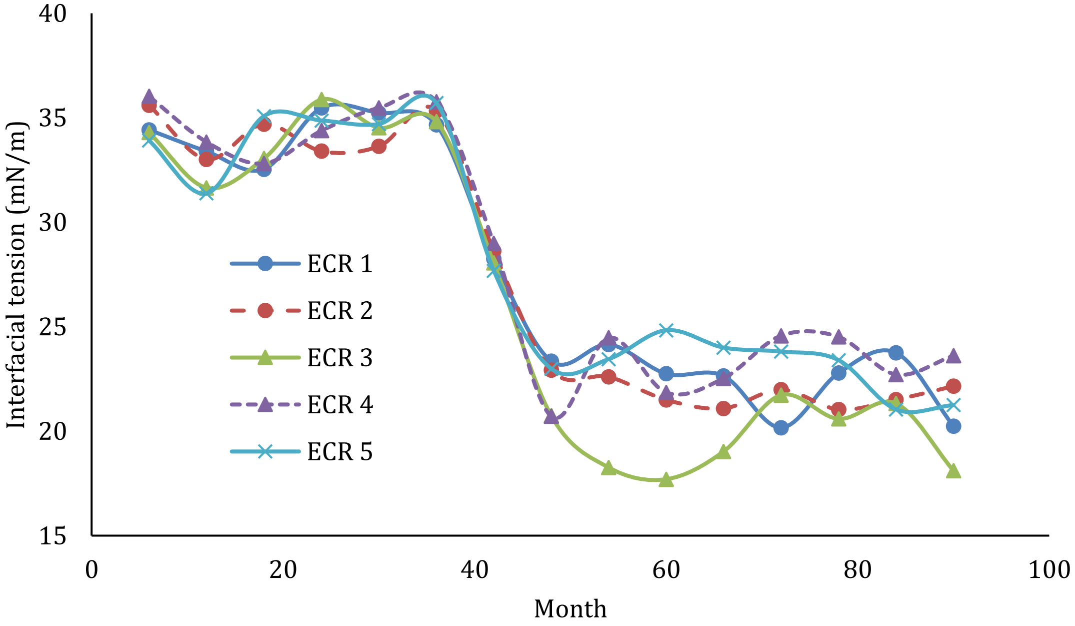
	Maintenance Term, Month														
	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90
Analysis								**TCR 6**							
WC	21	27	24	19	23	24	35	35	41	39	33	31	30	30	31
IFT	35.47	31.49	34	34.36	34.76	27.42	25.08	24.13	24.59	24.83	24.36	23.42	23.78	23.39	20.85
DS	59	57	57	57	42	40	39	21	31	32	39	36	41	33	38
CO_2	334	203	1197	1094	1433	677	466	789	1,011	766	1042	1077	1069	939	905
								TCR 7							
WC	20	25	25	36	23	24	21	24	22	25	28	32	31	31	21
IFT	34.59	31.94	32.86	36.56	33.36	35.94	27.66	19.7	20.48	20.47	20.81	18.46	19.46	19.7	21.12
DS	50	48	48	56	49	42	42	50	54	50	57	42	48	36	53
CO_2	248	174	100	787	1064	971	781	197	365	553	507	655	830	996	737
								TCR 8							
WC	33	33	38	35	17	32	30	28	26	29	10	32	31	31	43
IFT	35.06	32.88	34.32	36.47	34.56	35.23	27.64	20.37	19.13	18.68	39.22	20.57	18.68	19.27	25.72
DS	47	43	41	60	45	33	40	39	44	50	51	50	45	34	31
CO_2	214	125	761	620	1026	1093	781	249	512	651	391	771	885	1089	656
								TCR 9							
WC	23	14	31	29	16	28	30	24	58	56	42	39	38	38	39
IFT	34.87	35.69	33.37	31.54	34.47	34.46	35.2	20.26	26.9	26.09	24.56	25.2	22.77	22.08	21.74
DS	60	60	60	60	55	42	36	49	32	37	35	37	32	36	29
CO_2	327	281	175	910	757	877	793	201	500	721	1145	1525	1146	958	1113
								TCR 10							
WC	52	39	25	34	32	26	25	21	35	35	31	30	33	30	19
IFT	33.8	35.95	34.05	36.08	29.16	25.88	23.96	23.97	24.18	24.41	21.51	24.31	25.1	22.35	24.36
DS	35	47	59	41	50	35	49	47	35	51	52	40	34	33	46
CO_2	281	555	1661	1,219	1417	628	496	620	650	749	1015	932	1125	889	281



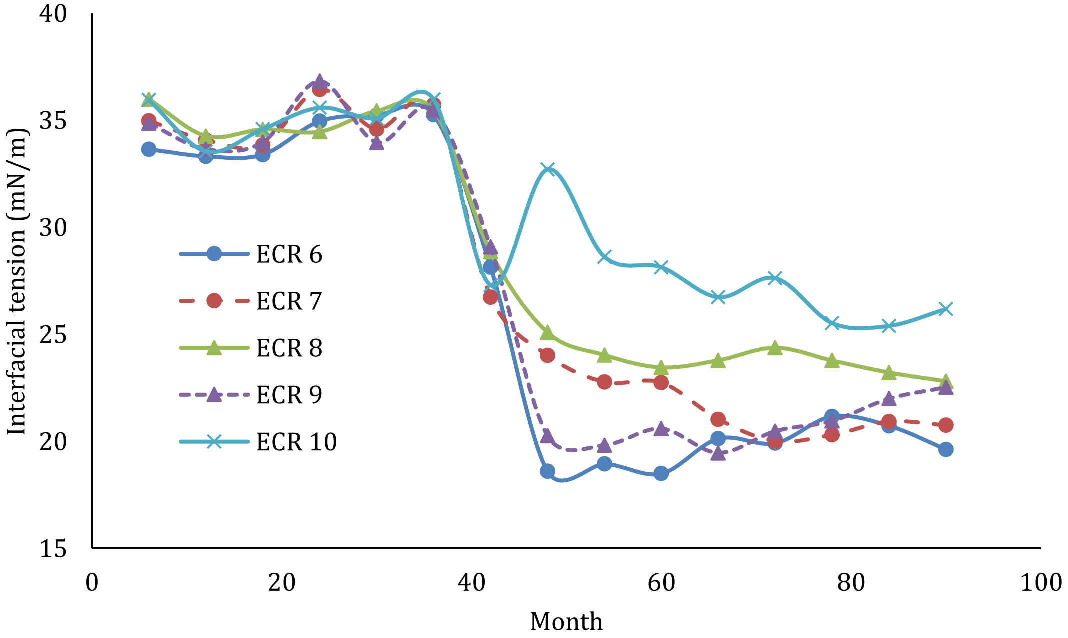
(a)

(b)

Figure 5: Water content of transformer oil for (a) ECR 1 to 5 and (b) ECR 6 to 10.

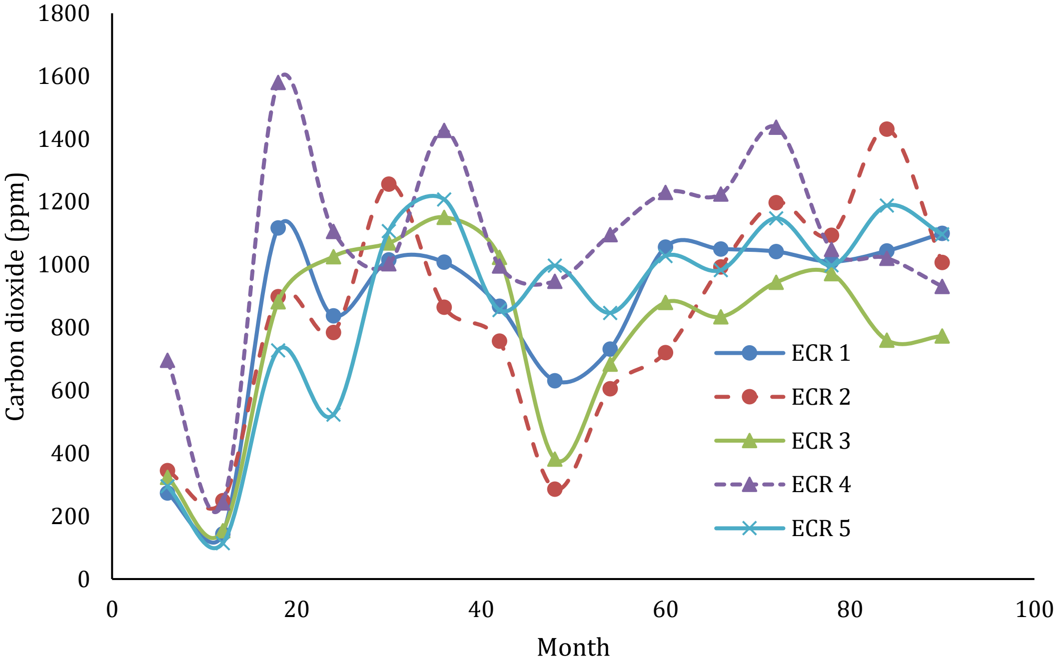


(a)

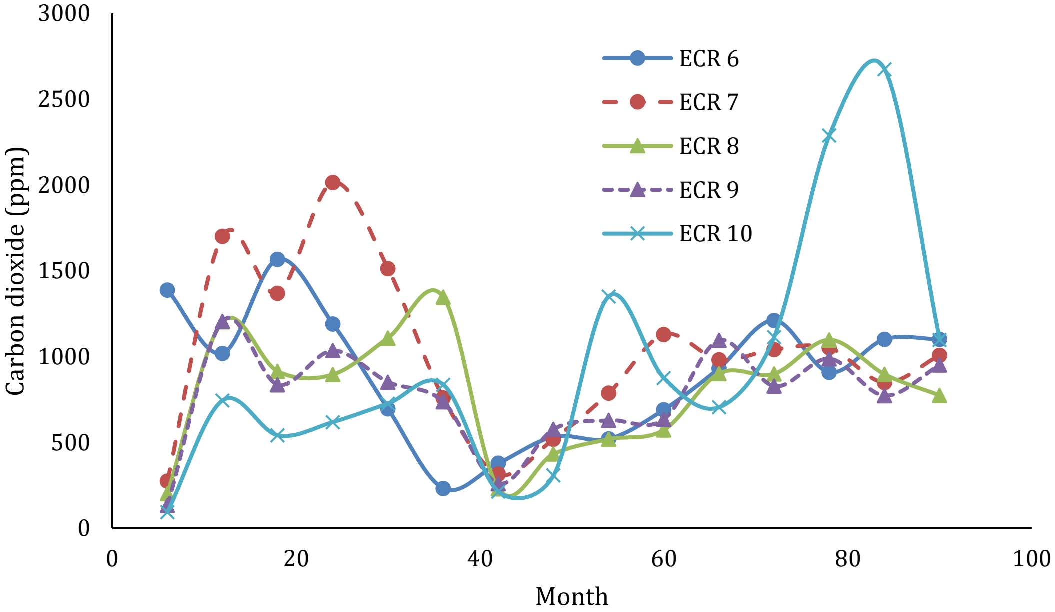


(b)

Figure 6: Interfacial tension of transformer oil for (a) ECR 1 to 5 and (b) ECR 6 to 10.

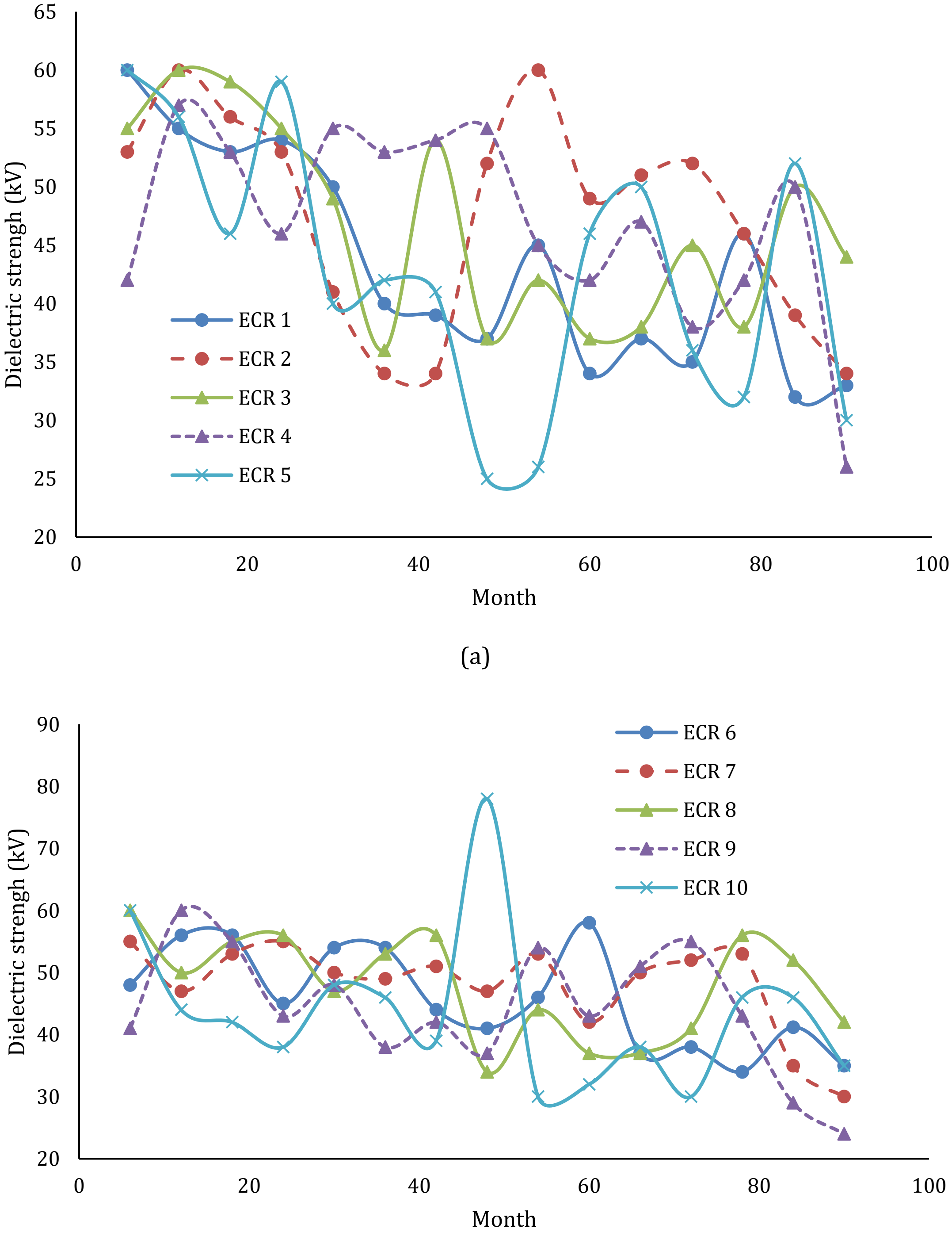


(a)



(b)

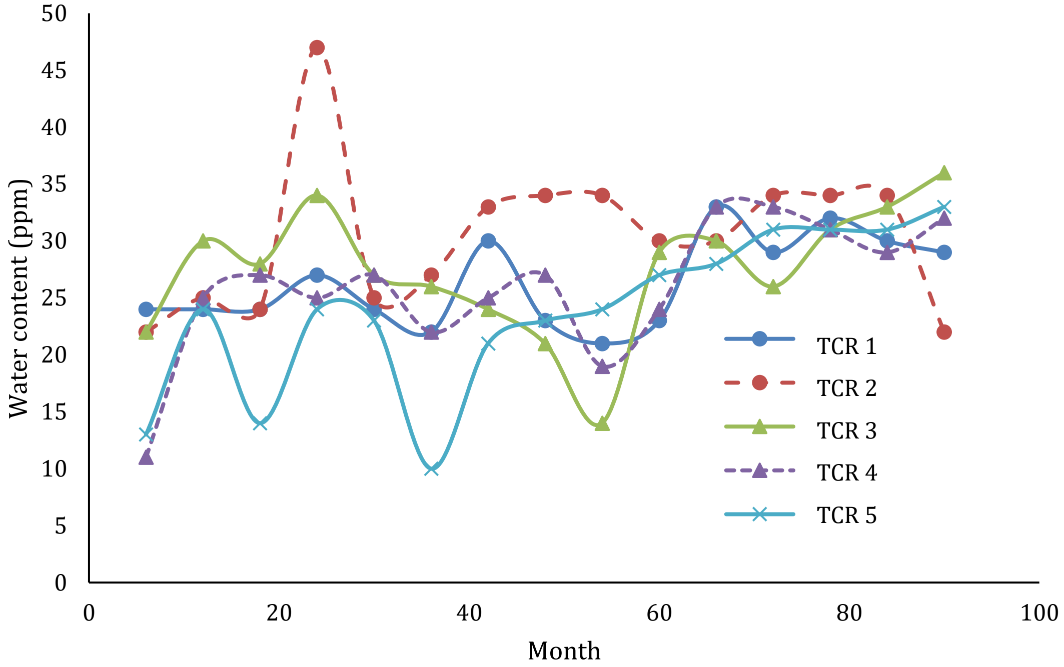
Figure 7: Carbon dioxide of transformer oil for (a) ECR 1 to 5 and (b) ECR 6 to 10.



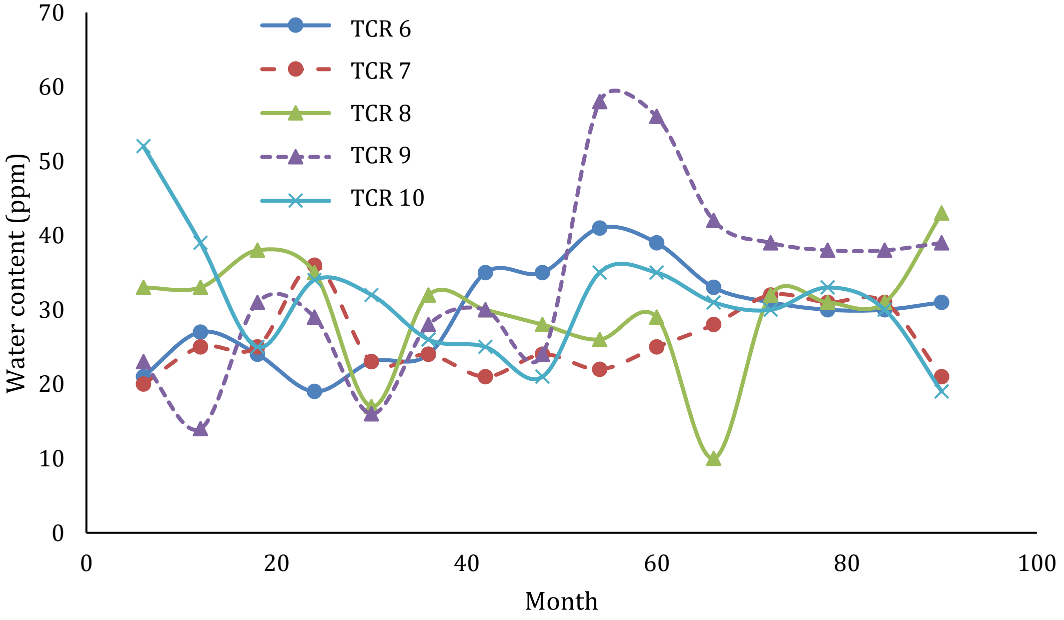
(a)

(b)

Figure 8: Dielectric strength of transformer oil for (a) ECR 1 to 5 and (b) ECR 6 to 10.



(a)



(b)

Figure 9: Water content of transformer oil for (a) TCR 1 to 5 and (b) TCR 6 to 10..

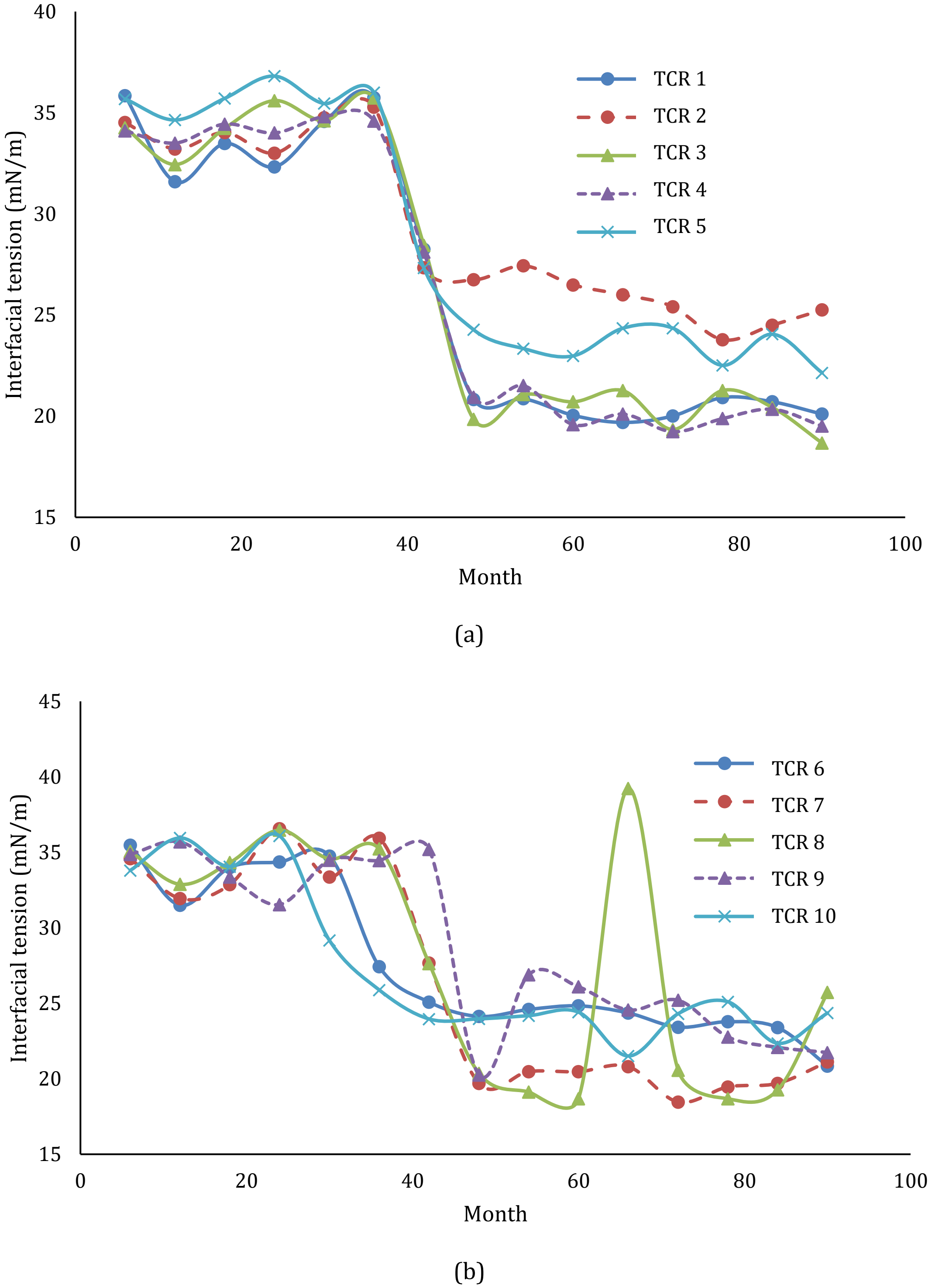
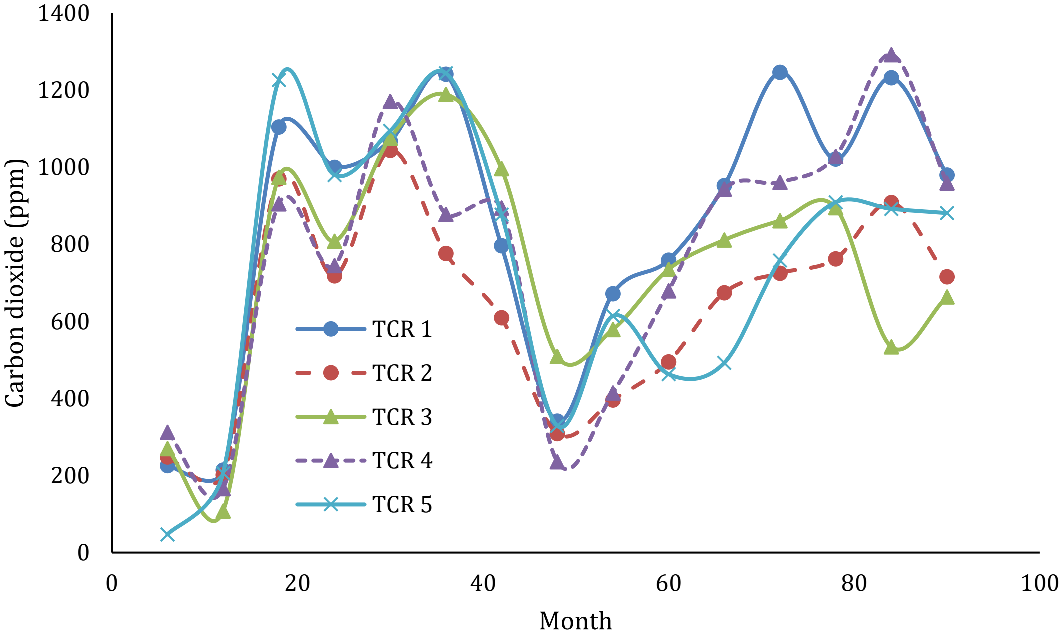
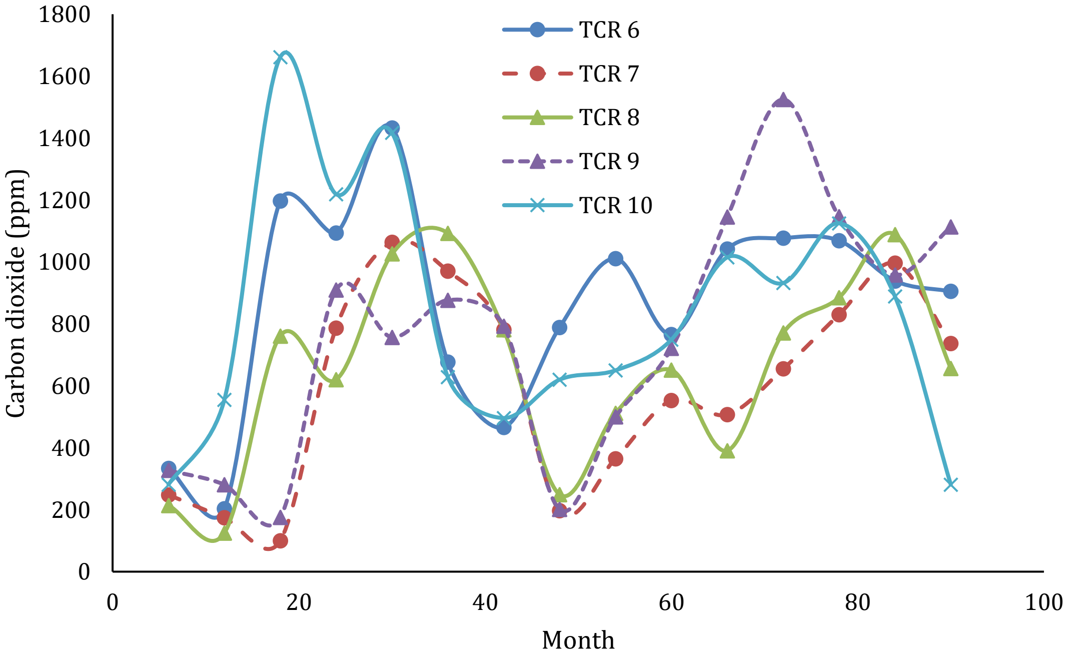


Figure 10: Interfacial tension of transformer oil for (a) TCR 1 to 5 and (b) TCR 6 to 10.

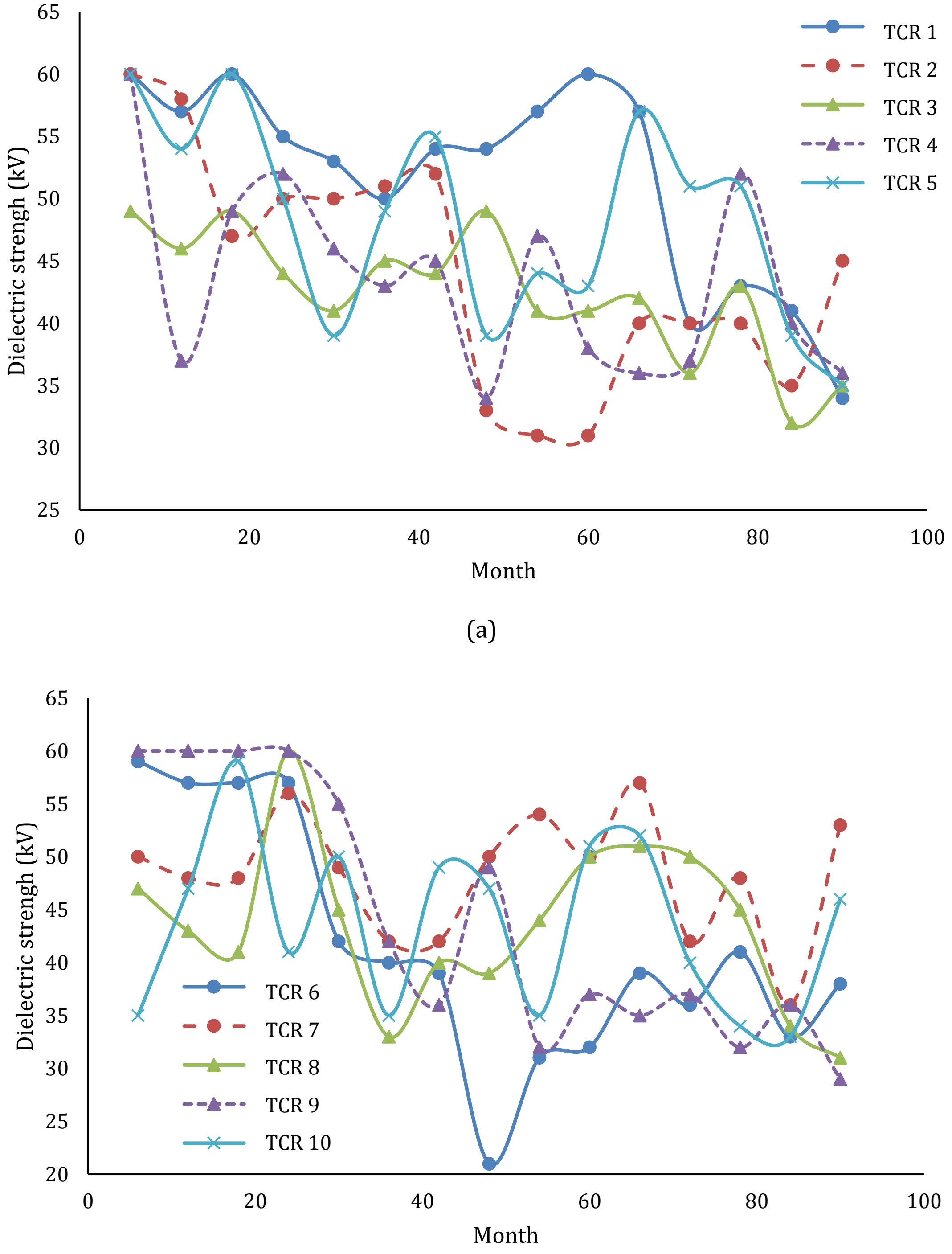


(a)



(b)

Figure 11: Carbon dioxide of transformer oil for (a) TCR 1 to 5 and (b) TCR 6 to 10.



(a)

(b)

Figure 12: Dielectric strength of transformer oil for (a) TCR 1 to 5 and (b) TCR 6 to 10.

Table 9: Rate of analysis for ECR.

Train	Rate			
	Water content, ppm/month	Interfacial tension, mN/m/month	CO_2, ppm/month	Dielectric strength, kV/month
ECR 1	0.1958	-0.1981	6.8643	-0.2875
ECR 2	-0.0851	-0.2074	7.8143	-0.1351
ECR 3	0.0940	-0.2289	3.1631	-0.1935
ECR 4	0.1440	-0.1819	3.1917	-0.1762
ECR 5	0.0286	-0.1854	9.0280	-0.2220
ECR 6	0.0798	-0.2280	-1.7625	-0.2136
ECR 7	0.2327	-0.2276	-3.4786	-0.1613
ECR 8	0.1548	-0.1885	0.7274	-0.1446
ECR 9	0.1875	-0.2198	18.1400	-0.1702
ECR 10	-0.0280	-0.1391	2.3500	-0.1440
Average	0.1310	-0.2005	6.5424	-0.1848

Table 10: Rate of analysis for TCR.

Train	Rate			
	Water content, ppm/month	Interfacial tension, mN/m/month	CO_2, ppm/month	Dielectric strength, kV/month
TCR 1	0.0827	-0.2208	6.2613	-0.2310
TCR 2	0.0446	-0.1443	2.7470	-0.2435
TCR 3	0.0619	-0.2312	1.7899	-0.1500
TCR 4	0.1423	-0.2344	6.6679	-0.1387
TCR 5	0.2065	-0.2009	2.2917	-0.1637
TCR 6	0.1381	-0.1683	4.3185	-0.2905
TCR 7	0.0446	-0.2279	5.0917	-0.0327
TCR 8	-0.0119	-0.1884	4.1929	-0.0774
TCR 9	0.2935	-0.1826	10.3800	-0.0397
TCR 10	-0.1405	-0.1578	-1.5679	-0.0667
Average	0.1332	-0.1957	4.9737	-0.1434

4.0 CONCLUSION

The issues relating to transformer oil was analysed and identified from data collected over a period of 90 months. As transformer oil has a life cycle of 30 years and does not require replacing, filtration was found to be the most effective maintenance method. The predictive maintenance schedule proposed was developed based on actual analytically data in correlation to time. A linear relationship was used to observe the pattern and trend of the oil analysis. The transformer oil of ECRs require earlier maintenance than TCRs although they share the same product expiry of 30 years. Based on the patterns and trends observed, a predictive maintenance strategy can be implemented which will reduce the risk and possibility of train failure due to a faulty transformer. Oil filtration was found to improve water content, IFT, CO_2, and dielectric strength. Since the data was collected from actual operations, the uncertainty of the values is noted. Thus, the trends and patterns are useful for implementing a predictive maintenance strategy. Standard maintenance procedures may be applied for the transformer oil drain and refilling for oil samples taken. Our method of developing strategy a predictive maintenance schedule can be used by other operators running the same train model.

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