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# Study on Correlation Among Oil Dielectric Characteristics, Dissolved Gases, and Operating Life of 150 kV Power Transformer

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*Abstract:* Power transformer undergo aging overtime that degrades its insulation system. Oil-immersed paper insulation degradation in transformer can be assessed through the change in oil characteristics and the dissolved gases. Data related to these parameters are abundant, but study on correlation among these parameters and the operating time of power transformer is still limited. This paper presents statistical insights into aging of transformer insulation system through oil characteristics, dissolved gases and the operating time of transformer. As much as 219 in service 150 kV transformers population testing data were included in this study. The data was analyzed using linear regression correlation analysis to Figureure out the dependency of each parameters. Statistical correlation between each properties of oil insulation, dissolved gases and operating time were carried out. There are some oil properties that have correlation with operating time, which are color scale, IFT and acidity. Moreover, color scale, IFT and acidity shows dependency among them. IFT tends to gradually decrease while acidity increases as operating time trend rises. On the other hand, operating time are also highly correlated with CO and $CO_2$, which are commonly known as the main product of paper insulation degradation in transformers. Correlation among prior correlated parameters found that CO is strongly correlated with color and IFT. Subsequently, a high correlation coefficient of parameter to operating time could be interpreted that the ageing process happens during the life of a transformer changes certain parameters which these changes should be noticed for better decision making whether the transformer still feasible to be used in the system with certain maintenance or should be replaced.

*Keywords:* power transformer, insulation aging, dissolved gasses, operating time, oil dielectric characteristics.

## 1. Introduction

### A. Power Transformer

Transformer commonly known as one of the most important and expensive equipment in electrical system [1]. It is expected to be operated for years in maintaining the reliability of power system. The damage or explosion of transformer may occur faster than expected. Preventing transformer from early failure could be done by keeping the insulation system in good performance. During operation, transformer experiences ageing that causes deterioration of its insulation system. Ageing process consists of oxidation, pyrolysis and hydrolysis that subjected to transformer and its insulation system. All the process will decrease the performance of transformer and influenced by the presence of water, oxygen and temperature [2]. Those factors will affect the insulation system by generating ageing products that will continuously decrease the quality of insulation and the remaining life of transformer. Insulation attacked by ageing will work ineffectively and is likely to be failed. An effective assessment method is urgently needed to extend transformer lifetime and prevent the failure [3-4].

Insulation system of transformer generally consists of liquid and solid insulation. The liquid type of transformer insulation system especially is mineral oil and the solid type is cellulose. The previous research indicated that transformers failure mostly caused by insulation system breakdown. Moreover, transformer lifetime depends practically on its cellulose insulation. There

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are basically two factor that restrict the operating time of transformer which are ageing of oil-immersed cellulose insulation and the degradation of its mechanical strength [5-6].

Paper insulation is difficult to be examined directly since the transformer should be dismantled first to get the sample of cellulose. Otherwise oil insulation is easily taken from transformer tank to be inspected without damaging any part of it. Since oil insulation is containing ageing products from both of oil and cellulose insulation and handily attainable, assessing insulation system condition could be solved by interpreting the result of oil testing parameters. The interpretation of its insulation condition could be used as reference to decide whether the transformer should be replaced or still in its safe conditions [7-9]. All the actions that taken based on oil interpretation condition could be used to manage the transformer assets [10].

The common way to make interpretation of different oil test parameters that related to transformer oil condition is refer to IEC 60422 which classify the oil transformer conditions into three different conditions which are good, fair and poor based on its test parameters [11]. The latest version of IEC 60422 is made in 2013 as the improvement of the previous edition in 1973, 1989 and 2005 [12-14]. It explains the limit value of each different conditions in detail of different voltage levels, changes in value range and testing recommendation.

Another approaches in interpreting oil condition based on trends of oil test parameters were carried out in previous researches. Trend of DGA in operating time of transformer shows that CO and $CO_2$ will gradually increases as the transformer operated [1][9][11][15-19]. On the other hand, some dielectric characteristics of oil insulation indicates ageing pattern with its strong correlation to transformer operating time. Acidity, IFT and color found to be potential parameters to indicate ageing in transformers [10][11][18][20-26]. It could be concluded since acidity, IFT and color tend to be increased as transformer operating time getting longer [10][18][26][27].

References and recommendations from international papers, journals and standards are useful as the insight either for practical or theoretical in the field of transformer. However, assessment and maintenance ageing of in-service transformer needs an internal insight based on its own oil database. By analyzing transformer oil test result database enhanced with international recommendations, monitoring conditions of transformer would be better.

This paper will discuss correlation among transformer oil parameters and the operating time of power transformer, and will give insights into aging of transformer insulation system through oil characteristics, dissolved gases and the operating time of transformer. All the parameters discussed in this paper are from oil test databases of 219 Indonesian oil-immersed paper insulation in service transformers with primary voltage of 150kV. Correlation of each parameters will be discussed along with its scatterplots.

### *B. Oil-Immersed Paper Insulation Ageing*

Transformer windings is insulated by cellulose and immersed into mineral oil. By the time transformer commissioned, the whole insulation system gradually be interacted by oxygen, water and heat as the main factors that cause ageing [10]. Aging process which caused by those factors respectively are known as oxidation, hydrolysis and pyrolysis. All the process definitely will degrade the quality of insulations until its characteristics value is below its appropriate limit value. Aging in cellulose predominantly subjected to water through hydrolysis whilst oil subjected to oxygen through oxidation [15]. Each occurrence during oil-immersed paper insulation aging is influenced by a complicated interplay of oxidation, hydrolysis and pyrolysis that accelerated by temperature. Some common products from oil and cellulose ageing are hydrocarbon, hydrogen, water and carbon oxides. Hydrogen ($H_2$) and hydrocarbons ($C_2H_2$, $C_2H_6$, $CH_4$ and $C_2H_4$) are generated by ageing that accelerated by overheating [15] [16]. Oxidation and hydrolysis of cellulose produce water, CO and $CO_2$ as its main product. Another effects of ageing are changes in oil properties such as darker oil color, degradation of IFT, breakdown voltage and acidity. The darker oil color means the higher amount of contaminants dissolved in oil such as particle, gas, water, sludge, etc. as the result of oil oxidation [22-24]. The presence of contaminants will also increase its acidity level and decrease its IFT.

**B. Transformer Under Study and Testing**

*A. Power Transformer Sample*


Figure 1. Example of 150 kV transformer used in this study

Power transformer is regularly maintained by testing its insulation properties. There are commonly two kinds of transformer oil insulation testing which are DGA and dielectric characteristics. The DGA testing parameters consists of $H_2$ (hydrogen), CO (carbon monoxide), $CO_2$ (carbon dioxide), $CH_4$ (methane), $C_2H_6$ (ethane), $C_2H_2$ (acetylene), and $C_2H_4$ (ethylene). While the parameters testing the dielectric characteristics are water content, breakdown voltage, color, inter facial tension and acidity. The sample data of the correlation analysis is a test parameter performed on an in-service transformer which is seen in Figure.1. Those transformers have a primary voltage of 150kV and a voltage ratio of 150 / 20kV or 150 / 70kV. The age of the transformer varies from 0 to 30 years with details as in Figure. 2.

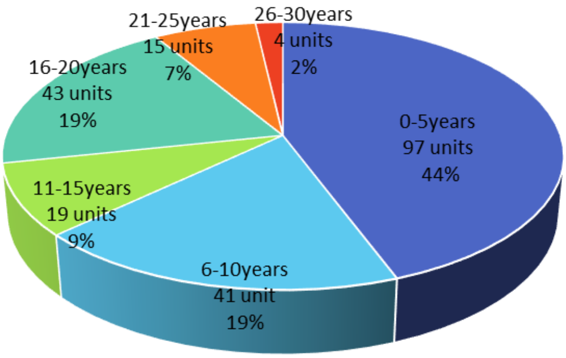



Figure 2. Transformer Age Population

*B. Measurement and Testing*

*B.1. Dissolved Gasses*

Oil insulation of an in-service transformer is tested routinely as one of many regular activities to maintain the transformer. Dissolved gasses in oil should be tested to interpret how far ageing ruins the whole insulation system. Dissolved Gas Analysis (DGA) of insulating oil is universally used and considered as an important indicator of a transformer's overall condition all over the world [28]. Analysis of the type and concentration of gas contained in the oil sample is done with Gas Chromatograph HP 6890 as shown in Figure 3.

The procedure to extract the gas from the oil sample refers to the IEEE and ASTM standards [26] [27]. The limit value of all the gases and four difference conditions based on TDCG are shown in Table 1 according to IEEE C57.104-2008.

Figure 3. Gas Chromatograph HP 6890

Figure 4. Oil sample in vials

Table 1. DGA interpretation according to DGA IEEE C57.104 2008

| Condition | $H_2$ | $CH_4$ | $C_2H_2$ | $C_2H_4$ | $C_2H_6$ | CO | $CO_2$ | TDCG |
|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 120 | 1 | 50 | 65 | 350 | 2500 | 720 |
| 2 | 100-700 | 121-400 | 2-9 | 51-100 | 66-100 | 351-570 | 2500-4000 | 721-1920 |
| 3 | 701-1800 | 410-1000 | 10-35 | 101-200 | 101-150 | 571-400 | 4001-10000 | 1921-4630 |
| 4 | >1800 | >1000 | >35 | >200 | >150 | >1400 | >10000 | >4630 |

*B.2. Dielectric Characteristics*

Besides DGA, dielectric characteristics is another regular testing that usually done in transformer assessment. Dielectric characteristics consists of many parameters related to oil properties [11]. In this study, the parameters restricted to only breakdown voltage, color scale, acidity, IFT and water content. Each parameter has its own difference way of testing with also difference method and instrument. Limit value for all parameters is difference and those limit could be used to assume the condition if oil insulation [11]. All the conditions and standard used to measure each parameter is shown in Table 2.

Table 2. Dielectric Characteristics Standards of 150 kV Transformer [11]

| Characteristics | Good | Fair | Poor | Standard |
|---|---|---|---|---|
| Acidity | <0.1 | 0.1-0.2 | >0.2 | IEC 62021 |
| Interfacial Tension | >28 | 22-28 | <22 | ASTM D971-99a |
| Breakdown Voltage | >50 | 40-50 | <40 | IEC 60156 |
| Color Scale | <3.5 | <3.5 | >3.5 | ISO 2049 |
| Water Content | <5 | 5-15 | >15 | IEC 60814 |

*a. Water Content*

The presence of water in oil insulation will affect the lifetime of transformer by reducing the condition of its insulation system. Moisture of the atmosphere could be absorbed by the insulation and decrease the breakdown voltage of the oil. Aging process is another source of water in insulation as dominant product through hydrolysis. Maximum amount of water in oil based on IEC 60422 2013 is 20 mg/kg. Water content in oil could be measured according to IEC 60814. In this study, water dissolved in oil measured by using Megger KF875 as shown in Figure. 5 and Karl Fischer method. Oil sample was taken by syringe that have been sterilized before then the oil is sprayed into testing liquid in Megger KF875.

Figure 5. Megger KF875

*b. Color Scale*

Degradation of insulation system will cause oil color darker. The measurement method of oil insulation color scale is based on ISO 2049. Oil color scale used in this study is ASTM D1500 as shown in Figure. 6. Maximum color scale according to IEC 60422 2013 is 3.5.Oil color is a visual and complementary indicator to other critical characteristics in determining the aging condition of oil insulation. Oil sample placed in a small sterile acrylic container then it is put in Loviband PFX195, tintometer as shown in Figure 7. to be examined.

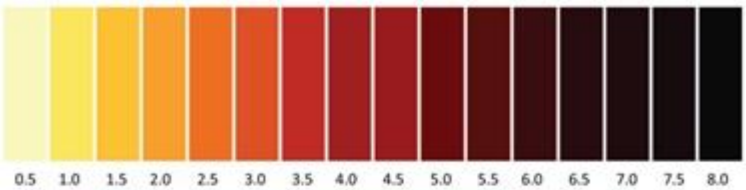


Figure 6. ASTM D100 color scale.

Figure 7. Loviband PFX195, Tintometer

*c. Interfacial Tension*

Interfacial tension measured by tensiometer as shown in Figure. 8. Oil insulation is still safe to be used when its interfacial tension is more than 3.5 dyne/cm. Tensiometer firstly calibrated by measuring the water tension in its container until the tension reaches 70 dyne/cm. Oil sample is slowly dropped into the container using syringe. A small metal triangle ring is dipped into the water then it is lifted and the value of oil interfacial tension will be shown in monitor as soon as the metal pass the boundary surface between water and oil.

Figure 8. Tensiometer

*d. Breakdown Voltage*

Breakdown voltage is the most important characteristics for electrical equipment. Ageing process will decrease dielectric characteristics and mainly breakdown voltage. According to IEC 60422 2013 minimum standard for oil insulation breakdown voltage is 50 kV/2.5mm. Breakdown voltage could be measure using Megger OTS 80 AF/2 as shown in Figure. 9. Oil sample is poured in the container that contained a pair of half cylindrical electrode with 2.5mm gap in between. The container then placed into the instrument and the voltage is increased as much as 2kV/s until the oil insulation reaches its breakdown voltage.

Figure 9. Megger OTS 80 AF/2

*e. Acidity*

Acidity is defined as neutralization value or how much mgKOH/g that should be added into oil to make the oil neutral. The value of acidity is affected by ageing and its products specifically contaminants or constituents. Acidity is tested using 702 SM Titrino by Metroohm as seen in Figure. 10. according to IEC 62021. Oil insulation is still in good performance if the acidity level less than 0.2 mgKOH/g.

Figure 10. 702 SM Titrino, Metroohm

*B.3. Typical Data of Power Transformer Oil Characteristics and Dissolved Gases*

Because of the limitation in space, the data shown here are only 14 typical data of power transformer operating time, dissolved gases, and oil dielectric characteristics as shown in table 3, while the analysis in this study used all 219 in service 150 kV transformer data.

Table 3. Typical data of power transformer

| Operating Time (Years) | Dissolved Gases | | | | | | | | Oil Dielectric Characteristics | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $H_2$ (ppm) | $CH_4$ (ppm) | $C_2H_2$ (ppm) | $C_2H_4$ (ppm) | $C_2H_6$ (ppm) | CO (ppm) | $CO_2$ (ppm) | TDCG (ppm) | Water (ppm) | BDV (kV) | Color Scale | IFT(dyne/cm) | Acidity (mg KOH/g) |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 159.59 | 0 | 4.45 | 80 | 0.5 | 35.4 | 0.01 |
| 2 | 147.8 | 49.2 | 0 | 51.5 | 0 | 108.5 | 264 | 357 | 5.18 | 49.2 | 0.5 | 34.2 | 0.05 |
| 3 | 177 | 1308.8 | 36.2 | 3.1 | 0 | 25.7 | 819.9 | 1550.8 | 5.48 | 40.7 | 0.9 | 33.6 | 0.06 |
| 6 | 206 | 178 | 0 | 37 | 356 | 851 | 4946 | 1628 | 20.3 | 80.1 | 0.6 | 27.3 | 0.02 |
| 10 | 4.6 | 14.6 | 206.7 | 90 | 279 | 1049.6 | 4069.8 | 1644.5 | 14.13 | 84.9 | 6.1 | 19.7 | 0.15 |
| 12 | 0 | 87.02 | 0 | 13.84 | 96.68 | 832.85 | 3653.43 | 1030.39 | 4.84 | 80 | 6.4 | 10.7 | 0.16 |
| 15 | 0 | 0 | 0 | 46.06 | 0 | 504.75 | 3703.12 | 550.81 | 2.12 | 80 | 4 | 10.4 | 0.19 |
| 19 | 0 | 176.97 | 0 | 67.6 | 242.93 | 1438.07 | 6642.11 | 1925.57 | 3.28 | 80 | 6.6 | 10.6 | 0.18 |
| 19 | 43 | 225 | 0 | 30 | 684 | 434 | 5048 | 1416 | 12.98 | 90.5 | 2.5 | 26.4 | 0.02 |
| 24 | 0 | 210.6 | 0 | 0 | 130.7 | 825 | 859 | 1167 | 22.39 | 39.62 | 0.7 | 31.8 | 0.03 |
| 26 | 0 | 0 | 0 | 29 | 0 | 1518 | 942 | 1547 | 4.38 | 74.1 | 2.9 | 25.2 | 0.11 |
| 28 | 91.46 | 1.35 | 3.52 | 4.96 | 3.39 | 1106.21 | 6690.26 | 1210.89 | 36.89 | 50.8 | 4.1 | 16.8 | 0.16 |
| 30 | 0 | 7 | 3 | 42 | 5 | 1398 | 17977 | 1455 | 41.46 | 57.2 | 3.3 | 22.6 | 0.06 |

*B.4. Analysis Method*

This study collects measurement data of 219 power transformers population, which consist of operating time, dissolved gases, and oil dielectric properties. The dissolved gases and dielectric properties then be correlated to transformer operating time to obtain correlated parameters. After that, each of parameters from dissolved gases and dielectric properties is correlated with each other to get the dependency of each parameter.

Regression method is chosen to analyze the oil test result database of transformer population in this paper since it is the simplest technique yet effective to be used. As one of statistical methods, regression could indicate the correlation between two variable or more [29]. Linear is kind of correlation that only consists of two variable and called linear regression. By using the linear regression, relationship of two variable will be determined with its correlation coefficient (r). Correlation coefficient indicates how strong the correlation between two variables. The closer ‘r’ to +1 or -1, the stronger correlation will be. Positive correlation coefficient indicates positive correlation while negative correlation coefficient indicates negative correlation. The interpretation of correlation significance commonly depends on the variable, context and purpose of the research [30].

In this correlation analysis, "a" value of 0.05 (5%) is set. The value "a" denotes the maximum error limit specified as the reference, whereas "p value" is the value of error obtained. If the value of "p value" is smaller (<) or equal to (=) value "a" then the correlation is statistically significant. While the value of correlation coefficient (r) approaching -1 or +1 indicates a fairly strong correlation between these parameters. In this study, the value of "r" is considered significant when "r" is greater (>) than 0.34.

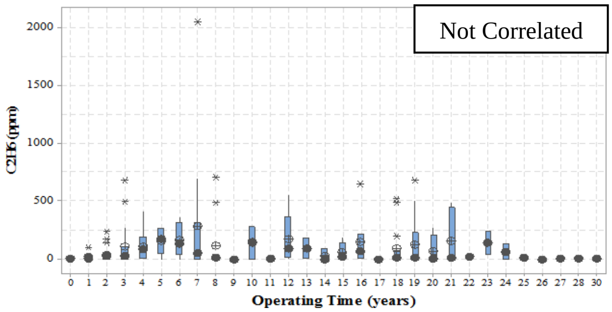
Different studies have been reported to investigate the relationship among transformer aging parameters. Study [10] carried out the linear regression correlation between oil dielectric characteristics and transformer in service age (year). Study [31] use linear regression correlation to find the significant predictor variables for total furan content and use it as degree of polymerization estimation. Article [32] discuss the use of linear regression to find the relationship between characteristic parameters and transformer life. Research in [16] use distribution analysis to statistically study the relationship of acidity and estimated degree of polarization. Another study [33] use the Weibull and gaussian distribution to investigate the withstand voltages of natural ester and mineral oil.

## 3. Results and Analysis

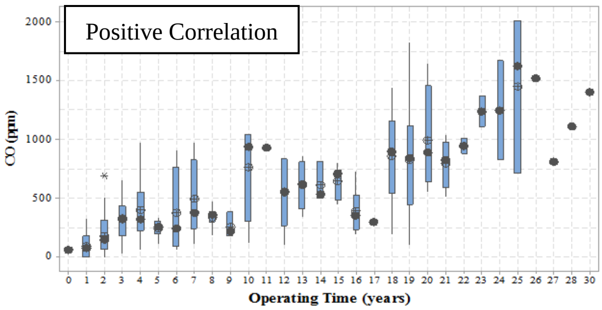
Power transformer measurement data population collected was analyzed according to aforementioned methods discussed in section 2. Linear regression correlation has been done to discover the relation between two parameters.

### *A. Correlation Between Dissolved Gases and Operating Life*

Calculating the correlation data between operating life and dissolved gas is carried out to know the effect of aging on transformer insulation condition. Dissolved gas in oil insulation is the result of aging from both paper and oil insulation itself. The dissolved gas comprises $H_2$ (hydrogen), CO (carbon monoxide), $CO_2$ (carbon dioxide), $CH_4$ (methane), $C_2H_6$ (ethane), $C_2H_2$ (acetylene), and $C_2H_4$ (ethylene).




(a)

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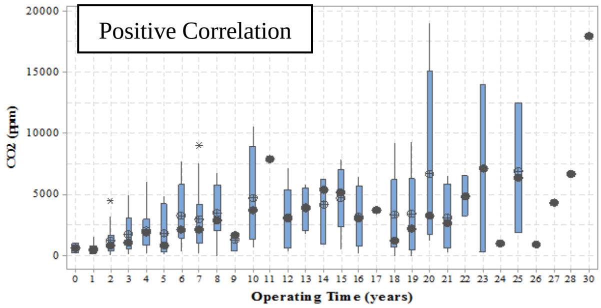



(c)

Figure 11. Dissolved gases trends from 150 kV transformer population. (a) $C_2H_6$; (b) CO; (c) $CO_2$.

Aging affects the amount of dissolved gas in oil insulation. The longer the transformer operating life, the higher ageing level of its insulation will be. By using linear regression method, the correlation coefficient between DGA and operating life is shown in Table 4.

Table 4. Correlation Coefficient between Dissolved Gases and Operating Life

| Gas (ppm) | r | p-value | |
|---|---|---|---|
| $H_2$ (Hydrogen) | 0.113 | 0.116 | Not correlated |
| $CH_4$ (Methane) | -0.003 | 0.968 | Not correlated |
| $C_2H_2$ (acetylene) | 0.146 | 0.040 | Not correlated |
| $C_2H_4$ (ethylene) | 0.082 | 0.237 | Not correlated |
| $C_2H_6$ (ethane) | 0.038 | 0.579 | Not correlated |
| CO (carbon monoxide) | 0.715 | 0.000 | Increased operating time leads to increased CO; can be used as an aging assessment parameter of transformer insulation |
| $CO_2$ (carbon dioxide) | 0.413 | 0.000 | Increased operating time leads to increased $CO_2$; can be used as an aging assessment parameter of transformer insulation |

Related to Table 4. $H_2$, $CH_4$, $C_2H_2$, $C_2H_4$ and $C_2H_6$ are not correlated to operating life. It could be concluded from its correlation coefficient which are less than 0.34. The presence of hydrogen and all the hydrocarbons are caused by overheating during ageing process. The amount of hydrocarbons is fluctuated since every hydrocarbon could be transformed into another form of hydrocarbon. Figure 11. (a). shows that $C_2H_6$ is not correlated to operating time like others hydrocarbons.

However, $CO_2$ and CO are strongly correlated to operating life. Correlation coefficient between CO and operating time is equal to 0.715. It means that CO has a fairly high correlation with operating time. This has been proven in previous studies [6], that the increase in CO is proportional to the operating time of transformer. The longer operating life of transformer, the higher CO contained in the oil will be. The correlation between CO and operating life can be seen in the graph in Figure 11.(b).

Correlation between $CO_2$ and operating time could be seen in Figure. 11.(c). The correlation coefficient between $CO_2$ and the operating time was 0.413. As the operating time getting longer, the amount of dissolved $CO_2$ in insulating oil is increasing. $CO_2$ is a dissolved gas after CO which has a positive correlation with the operating life of the transformer compared to other gases. The presence of CO and $CO_2$ in oil insulation is caused by ageing in insulation system of transformer. The basic material of cellulose is the main producer of CO and $CO_2$ dissolved in oil insulation. CO and $CO_2$ are mainly products of cellulose oxidation and hydrolysis besides water. Even though ageing of oil insulation also could produce CO and $CO_2$ in smaller amount. During ageing process, the increase of CO and $CO_2$ is faster in high temperature. The amount of CO and $CO_2$ are fluctuated but it still represents the insulation ageing level.

*B. Correlation Between Dielectric Characteristics and Operating Life*

Ageing in insulation will affect the dielectric characteristics. Based on the sample data, there were five parameters of dielectric characteristics which are color scale, acidity, breakdown voltage, IFT and water content. Correlation between operating life of transformer and all parameters is carried out. The result shows that color scale, acidity and IFT are highly correlated with operating life as shown in Table 5.

Related to Table 5, the color scale has a correlation coefficient of 0.502 to the operating life of transformer. The higher the operating life, the darker oil insulation will be. It happens because oil insulation contained a lot of contaminants during its operation which will cause the oil turns blackish. The correlation of operating life and color scale could be seen in Figure. 12. (a).

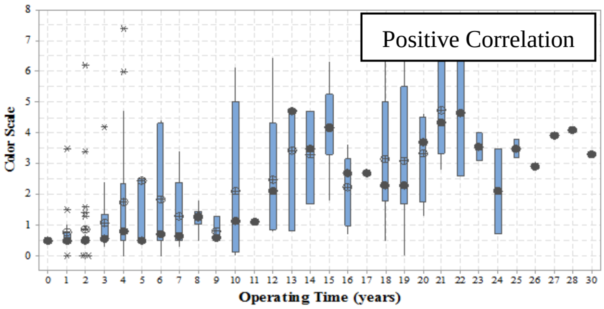
IFT could be used as another indicator that shows the degradation of oil insulation in early stage of ageing. As ageing happened in insulation system, all the contaminants which are small particles, varnish and sludge located in between oil and water surface so the IFT of oil insulation is decreased. The decrease of IFT is determined by oil insulation surface that easily cracked. From Figure. 12. (b), it could be seen the negative correlation between IFT and operating life of transformer with correlation coefficient about -0.463. It shows that the longer operating time of transformer, the smaller the IFT of oil will be.

Table 5. Correlation Coefficient between Dielectric Characteristics and Operating Life

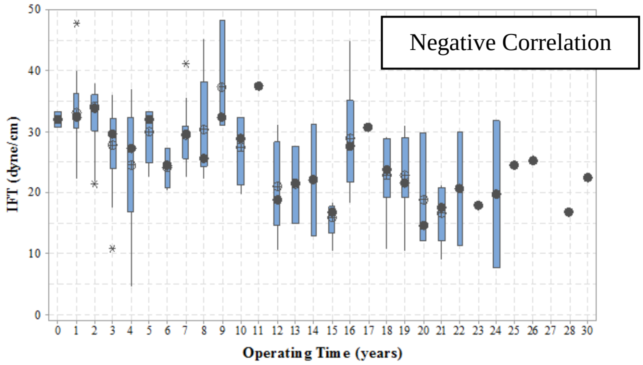
| Characteristics | r | P | |
|---|---|---|---|
| Water Content (ppm) | 0.22 | 0.001 | Not Correlated |
| Breakdown Voltage (kV) | -0.162 | 0.018 | Not correlated |
| Color Scale | 0.502 | 0.000 | Increased operating time leads to increased Color Scale; can be used as an aging assessment parameter of transformer insulation |
| IFT (dyne/cm) | -0.463 | 0.000 | Increased operating time leads to increased Interfacial Tension; can be used as an aging assessment parameter of transformer insulation |
| Acidity (mg KOH/g) | 0.358 | 0.000 | Increased operating time leads to increased Acidity; can be used as an aging assessment parameter of transformer insulation |

Some previous research found that acidity is correlated with operating life with correlation coefficient of 0.358. It shows the positive correlation between them as shown in Figure. 12. (c). The longer operating life of transformer, the higher acidity in oil insulation will be. Acidity slowly increase in the early stage of ageing and will exponentially increase after 35 years of operating time. Oxygen is the main factor that caused ageing in oil insulation through oxidation. The increase of acidity in oil insulation accompanied by the decrease of IFT.

From Figure 12. (d), it is generally shown that the correlation between water content to the operating time of the transformer. Although the trend of water content could be seen, the correlation coefficient is not significant. Generally, the increase of transformer operating life will increase the water content.




(a)

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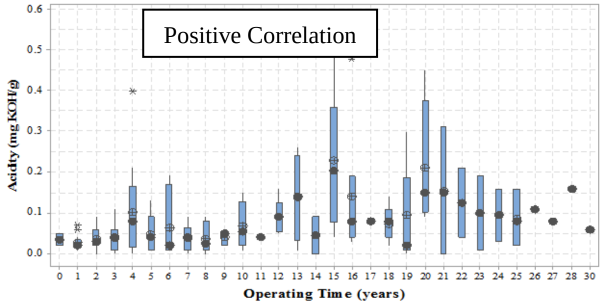


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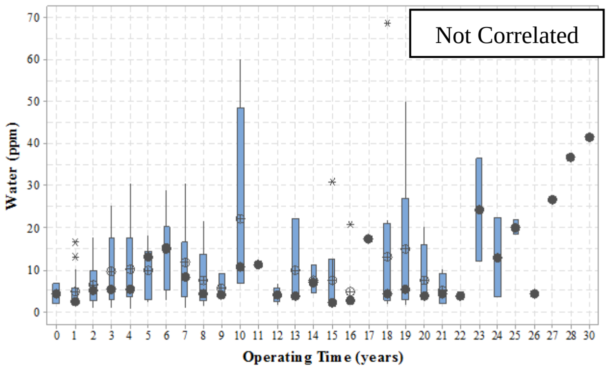



(d)

Figure. 12. Oil dielectric properties trends from 150 kV transformer population. (a) Color; (b) IFT; (c) Acidity; (d) Water content

*C. Correlation Among Aging Correlated Parameters*

Sub A and B explain five parameters of DGA and dielectric characteristics that correlated with operating life of transformer. Those correlated parameters are CO, $CO_2$, IFT, color scale and acidity. The next goal in this study is to investigate the correlation among the correlated parameters and how the correlation affects ageing process in transformer insulation. Table 6 shows the correlation coefficient among ageing correlated parameters. Using minimum standard for correlation coefficient more than 0.34, there are five high correlation among all correlated parameter which is shown in Figure 12. (a-d).

Table 6. Correlation coefficient of aging correlated parameters

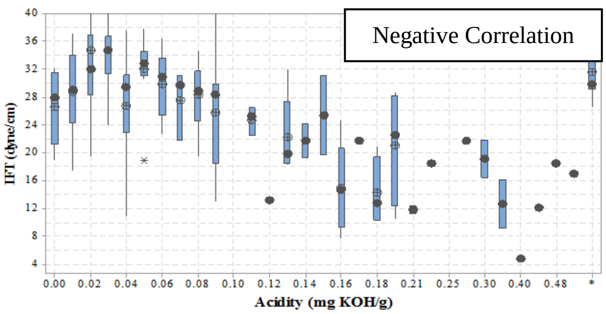
| | H2 | CH4 | C2H2 | C2H4 | C2H6 | CO | $CO_2$ | TDCG | Water | | BDV | Color | IFT | Acid |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H2 | 1 | 0.255 | 0.034 | 0.167 | -0.031 | 0.040 | 0.009 | 0.505 | 0.003 | | 0.319 | 0.037 | -0.054 | 0.051 |
| CH4 | | 1 | 0.040 | 0.373 | 0.457 | -0.041 | -0.038 | 0.525 | 0.051 | | -0.148 | -0.025 | -0.092 | 0.065 |
| C2H2 | | | 1 | 0.138 | 0.019 | 0.121 | 0.061 | 0.180 | -0.017 | | -0.145 | 0.157 | -0.221 | 0.191 |
| C2H4 | | | | 1 | 0.088 | 0.032 | 0.013 | 0.401 | 0.041 | | 0.030 | 0.007 | -0.127 | -0.116 |
| C2H6 | | | | | 1 | 0.029 | 0.118 | 0.465 | 0.211 | | 0.078 | -0.01 | -0.135 | -0.066 |
| CO | | | | | | 1 | 0.55 | 0.686 | 0.280 | | -0.054 | 0.486 | -0.459 | 0.269 |
| $CO_2$ | | | | | | | 1 | 0.404 | 0.367 | | -0.056 | 0.217 | -0.255 | 0.001 |
| TDCG | | | | | | | | 1 | 0.261 | | -0.163 | 0.342 | -0.419 | 0.173 |
| Water | | | | | | | | | 1 | | 0.058 | -0.086 | -0.069 | -0.12 |
| BDV | | | | | | | | | | | 1 | -0.118 | 0.034 | -0.057 |
| Color | | | | | | | | | | | | 1 | -0.625 | 0.498 |
| IFT | | | | | | | | | | | | | 1 | -0.519 |
| Acid | | | | | | | | | | | | | | 1 |

| | | | |
|---|---|---|---|
| 0,3-0,4 | | 0,6-0,7 | |
| 0,4-0,5 | | 0,7-0,8 | |
| 0,5-0,6 | | 0,8-0,9 | |

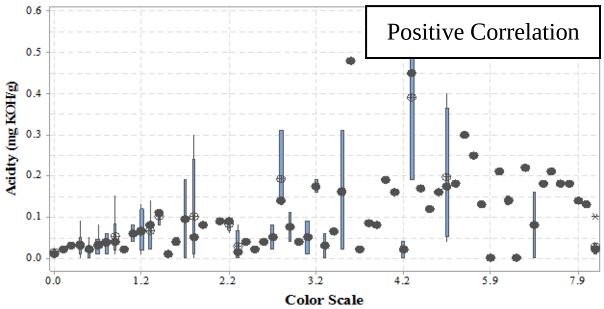
IFT and acidity has its own correlation related to Z.D. Wang (2013) previous research. Typical IFT trend with operating life of transformer has opposite correlation to typical acidity trend with operating life of transformer. The higher ageing level in insulation, the lower IFT and the higher acidity will be. Higher acidity is caused by a lot of contaminants where solid objects are one of them. Solid objects that lied in between boundary of oil insulation and water surely will decrease the IFT value. The correlation between IFT and acidity could be seen in Figure13. (a) with correlation coefficient -0.519.

The similar process is Figure out in correlation between acidity and color scale. As the oil insulation contains a lot of contaminants and causes high level in acidity, the color scale of oil insulation will be affected too. Once oil insulation subjected to stresses, its contents will not be as pure as before. Contaminated oil is shown by its darker color. Figure 13. (b) shown the correlation between color scale and acidity, the higher level of acidity, the higher color scale of its oil insulation.

Another strong correlation is found between IFT and color. The correlation could be seen in Figure 13. (c). From the graph displayed, it clearly show that the decrease of IFT would increase the color scale. The low level of IFT practically explains that ageing level of oil insulation is high. High level of ageing will cause the oil getting darker. It simply shows that the lower level of IFT, the more contaminant contained in oil, the higher color scale will be.

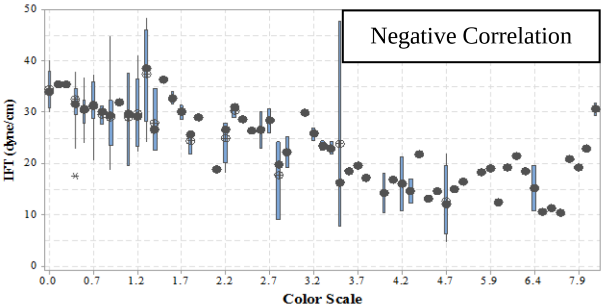



(a)



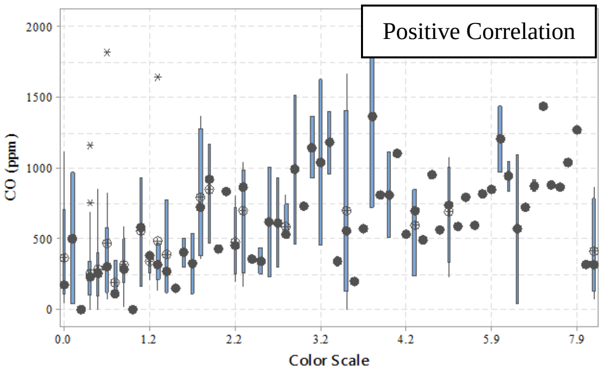
Positive Correlation
Acidity (mg KOH/g)
Color Scale


(b)



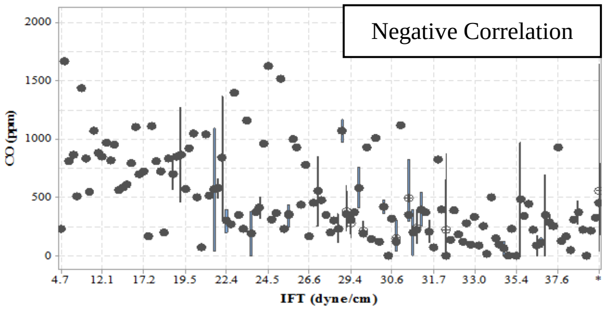
Negative Correlation
IFT (dyne/cm)
Color Scale


(c)



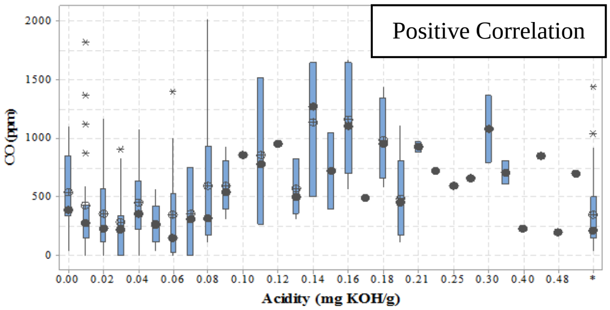
Positive Correlation
CO (ppm)
Color Scale


(d)



Negative Correlation
CO (ppm)
IFT (dyne/cm)


(e)



(f)

Figure 11. Dependency among correlated parameters. (a) Acidity and Interfacial Tension; (b) Color Scale and Acidity; (c) Interfacial Tension and Color Scale; (d) Carbon Monoxide and Color Scale; (e) Carbon monoxide and Interfacial Tension; (f) Carbon monoxide and Acidity;

Among all the DGA, there are only CO and $CO_2$ that have strong correlation with operating life of transformer. When the correlation among correlated parameters are carried out, CO is strongly correlated with color and IFT while $CO_2$ has no significant correlation with other correlated parameters. The higher amount of CO dissolved in oil, the darker oil color will be. Oil insulation getting darker because of the presence of contaminants that produced by one of ageing process which is oxidation. Oxidation in transformer insulation system which are oil and cellulose will produce CO. Ageing level in oil insulation is related to the amount of contaminants such as CO and it will cause the oil color getting darker. The amount of contaminants also related to the level of IFT. The higher amount of contaminants in oil, the lower IFT level will be. The correlation of CO to color and IFT respectively shown in Figure. 13. (d) and (e).

*D. Summary of Correlated Parameters*

The correlation analysis has been done to 219 population of power transformer testing data, and the correlated parameters result is summarized in Table 7.

Table 7. Result of Correlated Parameters

| Variable A | Variable B | r |
|---|---|---|
| Operating Time | Carbon Monoxide (CO) | 0.715 |
| Operating Time | Carbon Dioxide ($CO_2$) | 0.413 |
| Operating Time | Color Scale | 0.502 |
| Operating Time | Interfacial Tension | -0.463 |
| Operating Time | Acidity | 0.358 |
| Carbon Monoxide (CO) | Color Scale | 0.486 |
| Carbon Monoxide (CO) | Interfacial Tension | -0.459 |
| Acidity | Interfacial Tension | -0.519 |
| Acidity | Color | 0.498 |
| IFT | Color | -0.625 |

Carbon monoxide has the highest correlation to transformer operating time. From the experiments done by [34], CO gases was produced from thermal degradation of paper cellulose chain. Carbon oxides gas (CO and $CO_2$) was obtained as thermal aging result of paper insulation through oxidation process, the dielectric properties will decrease with the increasing duration and temperature of aging.

The degradation of the oil and paper are indicated by color of the insulation oil [34]. when the operating time increased, color of transformer oil become darker. This parameter can be used as an aging assessment parameter of transformer insulation.

Interfacial tension is measured to determine the presence of polar contaminants and oil decay products [35]. In general, inter facial tension of new mineral oil without aging is high and it decreases as per aging as well as electrical and thermal stresses [36].

Acidity is proven to have a high correlation to increasing operating time of transformer in previous experiments [10] [25]. Oxygen attacked the oil insulation producing acids through oxidation process [10][16][25]. The presence of acid is detrimental to solid insulation because it obviously will increases the probability of hydrolysis occurrence in cellulose. Moreover hydrolysis in cellulose will produce another acids, moisture, carbon oxides, furans etc. [10][16]. Oxidation and hydrolysis of insulation system that accelerated by temperature continuously happen during operating time of transformers and generate acid even more [25]. It is clearly explained that the increasing operating time of transformer will lead to the increasing of acidity level of oil insulation.

Acidity and IFT shows a contrary correlation to transformer operating time. The increasing of operating time will increase the acidity level and decrease the IFT in different rate. Acidity will slowly increase in early stage of transformer ageing and exponentially increase after the operating time of 35 years [10]. Otherwise the IFT will gradually decrease at the beginning of transformer operating time and remains almost constant after the age of 35 years in consequence of critical micelle concentration [10]. The combination of acidity and IFT will lead to better interpretation since IFT is more sensitive in the ageing early stage and subsequently acidity could be used to show the ageing late stage [10].

CO, $CO_2$, Acidity, IFT, and Color shows dependency among each other. This is because of the oil-paper insulation aging inside of the transformer through hydrolysis, pyrolysis, and oxidation processes. CO, $CO_2$, Acidity, IFT, and Color could be used as potential indicator of oil-immersed paper aging in transformer Dielectric Characteristics and Dissolved Gases [18,19].

## 4. Conclusion

We have studied 219 units of transformers focusing on dissolved gases and dielectric characteristics for different operating time. The investigation on correlation among them lead to the following conclusion:

- CO, $CO_2$, color scale, IFT and acidity have correlation with transformer operating time
- CO, $CO_2$, color scale, IFT and acidity shows dependency among them
- IFT tends to gradually decrease while acidity increases as operating time rises
- CO, $CO_2$, color scale, IFT and acidity could potentially be used as indicator to indicate insulation system
- CO also has strong correlation with color and IFT
- The higher amount of CO dissolved in oil will decrease the IFT level and increase the color scale

High correlation coefficient of parameter to operating time could be interpreted that the ageing process happens during the life of a transformer changes certain parameters, and these changes should be noticed for better decision making whether the transformer still feasible to be used in the system with certain maintenance or should be replaced. By knowing the ageing characteristics of our own oil test result database, more effective assessment and maintenance method for our asset could be produced. The ageing rate is shown by the result of linear regression between parameters and could be used to indicate transformer condition and for considerations to make suggestions and recommendation in transformer assessment. For further study, it would be better to analyze bigger transformer populations with more transformers. The measurement should be done carefully and validity of the result should be kept high.

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