Novel modeling of residual operating time of transformer oil

Mohamed A.A. Wahab, M.M. Hamada and G. Ismail
Electrical Engineering Department, Faculty of Engineering, Minia University, Minia, Egypt
A.G. Zeitoun
Electrical Engineering Department, Faculty of Engineering, Cairo University, Cairo, Egypt

This paper presents techniques developed to accurately model the characteristics of transformer oil for the purpose of predicting the effect of aging on these characteristics. Aging causes some of the transformer oil characteristics to violate the internationally specified limits. The purpose of this simulation is to develop alternative techniques to predict the operating time after which these characteristics would violate the limits. The results obtained from monitoring of twenty in-service power transformers for long period of operating time up to ten years have been implemented in developing the proposed models. The physical, chemical and electrical characteristics have been determined periodically by internationally specified testing methods. The patterns of violation sequence of the standard limits, against operating time, by different transformer oil characteristics have been revealed and the most common pattern has been determined. The definition of Residual Operating Time (ROT) of the different transformer oil characteristics has been introduced. The choice of transformer oil breakdown voltage ROT to represent that of the transformer oil characteristics has been justified. Modeling of ROT as a function of transformer oil breakdown voltage, total acidity and water content by multiple-linear regression has been proposed and verified. Also, polynomial regression model of ROT as a function only of transformer oil breakdown voltage has been given. The accuracy and applicability of these models and the different modeling techniques have been discussed and proved.

تزداد أهمية دراسة تأثير التقادم على الخصائص المختلفة لزيوت المحولات عندما تقترب من أو تتخطى هذه الخصائص القيم الحدودية المتفق عليها بالمواصفات القياسية العالمية لتشغيل الزيوت. في هذا البحث تم دراسة تأثير التقادم على الخصائص المختلفة لزيوت المحولات بدراسة عشرين محول بالخدمة و لمدد طويلة تصل إلى عشر سنوات وذلك بالإجراء الدوري للاختبارات القياسية العالمية للخصائص الفيزيائية و الكيميائية و الكهربية لزيوت هذه المحولات. تم اقتراح الأنماط المختلفة للتسلسل الزمني لتعدى قيم الخصائص المختلفة لزيوت المحولات للقيم المحددة بالمواصفات القياسية العالمية و تم تحديد النمط الأكثر شيوعا من بين هذه الانماط. أعطى تعريفا للزمن المتبقي لتشغيل زيوت المحولات وهو مدة التشغيل لهذه الزيوت من لحظة إمداد الزيوت أو تنقيتها إلي أن تبدأ قيم خصائصها في تخطى قيم المواصفات القياسية العالمية. وتم تحديد وتأكيد صحة اختيار زمن التشغيل الخاص بجهد انهيار العزل الكهربي لزيوت المحولات للدلالة على زمن تشغيلها وذلك بالاعتماد على الأنماط المختلفة للتسلسل الزمني لتعدي الحدود القياسية العالمية للخصائص. تم استنباط نماذج رياضية مبنية على النتائج المعملية لاستقراء الزمن المتبقي لتشغيل زيوت المحولات كدالة في كل من جهد انهيار العزل الكهربي لزيوت المحولات والحمضية الكلية ومحتوى المياه في الزيوت. وكذلك أستنبط نموذجا رياضيا لاستقراء الزمن المتبقي لتشغيل زيوت المحولات كدالة كثيرة الحدود في جهد انهيار العزل الكهربي لزيوت المحولات.تم تطبيق هذه النماذج الرياضية بالتعامل بأكثر من أسلوب تقني على نتائج اختبارات الزيوت لعدد من المحولات سواء كانت قد استخدمت أو لم تستخدم في استنباط هذه النماذج و قد أثبتت مناقشة النتائج دقة وقابلية تطبيق هذه النماذج الرياضية.

Keywords: Transformer oil, Modeling, Residual operating time, Breakdown voltage.

1. Introduction

The reliability of an electric power system depends strongly on those of its components. Transformer insulation has a great impact on its reliability. Transformer oil has proved to be very reliable for the last decades. However it is affected by normal and faulted operating conditions. Major faults in power transformers can cause not only catastrophic damages within the unit but also interruption of electricity supply resulting in large economic loss [1]. The new trend of investigation of transformer insulation is the development of diagnostic, measurement and monitoring techniques [2-6]. The aim of these techniques is to prevent insulation deterioration and to eliminate unexpected transformer outages. International Electro-technical Commission (IEC) and similar bodies put forward regulations on the levels of acceptance of the oil characteristics in the form of standard specifications. The in-service operating Time after which some or all characteristics violate the specified limits will be referred to as the Residual Operating Time (ROT). The prediction of ROT is of vital importance to plan adequate maintenance schedule and to prevent unpredicted outage of several transformers, which in turn increases the reliability of electric power supply. The occurrence of a disturbance in the transformer can be detected by the deviation of consecutive predicted residual operating times from the general trend.

The purpose of this paper is to introduce a model for the prediction of ROT for transformer oil characteristics. The patterns of the violation sequence of the different transformer oil characteristics with operating time are revealed depending on the monitoring results and discussed from the viewpoint of their effects on the operation of the transformers. According to these patterns, the transformer oil characteristic with longest operating time has been determined. The ROT has been formulated by treating the results obtained from monitoring all the transformers as those of a single equivalent transformer. This concept was first introduced by the authors in a previous publication [7]. The contribution of this study can be summarized in the following points:

(1) Proposal and verification of the violation sequence patterns of the standard specification limits for the different transformer oil characteristics.
(2) Introduction and definition of residual operating time ROT for the different transformer oil characteristics.
(3) Determination of the descriptive characteristic of the transformer oil deterioration.
(4) Development of novel models to predict the ROT of transformer oil characteristics.
(5) Justifying the applicability and validity of ROT models by implementing them on predicting transformer oil characteristics. The results of these transformers don't have to be considered in developing the models

2. Experimentation

The procedures of determining the breakdown voltage, total acidity, water content, ash content, viscosity and flash point are given in Ref. [8-13] respectively.

3. Results and discussion

3. 1 Transformer oil characteristics

The internationally accepted limits for transformer oil characteristics are given in Table 1. The results of tests mentioned in the previous section are obtained periodically against the time of measurement. The results of testing for the transformer oil (Tr. 15) are given in Table 2. In this case measuring of operating time starts after purification of the transformer oil and operating time is expressed in months. Table 2. shows the violated values and the operating time at which violation is recorded for the different transformer oil characteristics. The breakdown voltage decreases rapidly in the first three consecutive readings and after that the decrease becomes slow. This is explained by the respective change in the water content and agrees with describing the change in the breakdown voltage with the water content by the two-slope line proposed in Ref. [14]. The interdependence between total acidity and water content justifies that the breakdown voltage can also be represented as a function of total acidity, water content and operating time [7]. This means that the effect of transformer oil breakdown voltage on the operating time implicitly includes various time dependent transformer oil characteristics. The breakdown voltage attains its importance from the fact that it will be used in this study to provide long-term information about the condition of the transformer oil depending only on its present measurement.

Table 1 Internationally accepted limits for transformer oil characteristics.

Characteristic	Limits and units
Breakdown voltage	50-30 kV [8]
Water content	15-30 ppm [10]
Total acidity	0.03 mg KOH/gm oil [9]
Flash point	145°C [13]
Viscosity	For class I 16.5 cst at 4 0 ° C [15]

3.2 Residual operating time (ROT)

The ROT of a given characteristic will be defined as the time from the instant of measurement until this transformer oil characteristic violates the internationally accepted limit. Table 3 shows the measurement time and the residual operating time for the characteristics of transformer oil Tr. 15. The longest residual operating time is obtained for the breakdown voltage. From Table 3 it can be seen that the residual operating time of a given characteristic decreases with the increase of operating time. The zero residual operating time is the instant at which violation of the standard specification limit for a given characteristic has been recorded. The violation may occur before this time and this may be a source of error in the modeling of ROT. However, the periodical measurement by a reasonable period of time, especially when deterioration of transformer oil becomes noticeable, will decrease the probability of violation for long time before its detection. The accumulation of experimental results and treating them by the concept of a single equivalent transformer may alleviate the errors, which occurs due to the difference between actual and measured violation time. Also this indicates the importance of derivation of a model for ROT to prevent the operation of transformer with violated standard specification limits of different transformer oil characteristics. The characteristic that has the longest residual operating time (breakdown voltage) will be decisive for the formulation of ROT. If unpredicted disturbances occurred in the transformer the consecutive values of residual operating time for transformer oil characteristics will deviate much from the general prediction trend. Also depending on this time adequate maintenance can be managed and oil supply can be economized. The results presented in this paper are obtained from field measurements for practically stressed transformer oils. These transformer oils are expected to be subjected to all kinds of stresses during the course of monitoring.

3.3 Patterns of standard limits violation sequence

The variation of the transformer oil characteristics with operating time for the considered transformer oils and along the monitoring and measurement periods revealed that there are different sequences of violation of the standard limits which can be followed by the total acidity, water content and breakdown voltage. Nine patterns of standard limit violation sequences have been proposed and given in Table 4. They are selected to account for all kinds of combinations. The table shows the order of sequences of violation of different standard limits by different transformer oil characteristics. In pattern 7 the violation of the standard limits for the total acidity and water content is recorded at the same time. The percentage of occurrence of a given pattern is calculated as a ratio between the occurrence of this pattern to the total number of the cases recorded in which the violation of total acidity, water content and breakdown voltage have occurred. Table 4 shows the percentage of occurrence of the proposed patterns. From this table it can be seen that pattern (3) has the largest percentage of occurrence. This indicates that starting with violated standard specification of total acidity is the most common violation of the cases studied. There are zero percentage of occurrences of patterns (1) and (2). This indicates that there is a great dependence of the breakdown voltage on total acidity and water content while the reverse does not exist. Patterns (8) and (9) have zero percentage of occurrences. There is a rare occurrence of independent increase in water content (or total acidity) to a level that deteriorates the breakdown voltage without violation of total acidity (or water content).

Table 2 Transformer oil (Tr. 15) characteristics as function of time.

Operating time (Month)	Break-down (kV)	Water content (ppm)	Total acidity (mg KOH/ gm oil)	Viscosity (Engler)	Ash content	Flash point (° C)
0	73	17	0.014	1.6	Nil	149
21	54	30	0.016	1.6	Nil	149
27	52	55	0.03	1.6	Nil	149
36	37	61	0.048	1.6	Nil	149
39	34	65	0.096	1.6	Nil	150
45	30	66	0.14	1.6	Nil	150
48	30	65.5	0.14	1.6	Nil	150
51	29.5	66	0.142	1.6	Nil	150
54	30	66	0.16	1.6	Nil	150
57	29	66	0.168	1.6	Nil	150

Table 3 Measurement time and residual operating time (ROT) for the characteristics of transformer (15).

Measurement time (month)	Breakdown voltage ROT (month)	Water content ROT (month)	Total acidity ROT (month)
0	57	27	36
21	36	6	15
27	30	0	9
36	21		0
39	18		
45	12		
48	9		
51	6		
54	3		
57	0		

Table 4 Proposed pattern for the sequence of violation of internationally accepted specification limits and their percentage of occurrence.

Pattern number	Sequence of violation of international standard specification limits			
	First violated characteristic	Second violated characteristic	Third violated characteristic	Percentage of occurrence
1	Breakdown voltage	Total acidity	Water content	0.0 %
2	Breakdown voltage	Water content	Total acidity	0.0 %
3	Total acidity	Water content	Breakdown voltage	36.84 %
4	Total acidity	Breakdown voltage	Water content	5.26 %
5	Water content	Total acidity	Breakdown voltage	21.1 %
6	Water content	Breakdown voltage	Total acidity	5.26 %
7	Water content + Total acidity	Breakdown voltage	No third violation	31.58 %
8	Water content	Breakdown voltage	No third violation	0.0 %
9	Total acidity	Breakdown voltage	No third violation	0.0 %

This verifies the interdependence between water content and total acidity. Results given in Table 4 justify the conclusion that the breakdown voltage depends on water content and total acidity. Water content and total acidity depend on each other. All these characteristics are a function of operating time. In patterns (3), (5) and (7) the breakdown voltage has the longest operating time among other characteristics. This justifies the dependence on breakdown voltage residual operating time ROT to evaluate transformer oil characteristics.

3. 4 *Results of ROT as function of trans former oil characteristics*

The ROT for each characteristic will be used as the dependent variable while the breakdown voltage, total acidity and water content are considered to be independent variables. Figs. 1-a and 1-b represent the breakdown voltage ROT for transformer oils with low and high initial values of breakdown voltages respectively. The high values of breakdown voltage are considered to be from 63 kV and above while low values are below 63 kV. Figs. 2, and 3, give the total acidity and water content ROT for the transformer oils designated as oils with low initial breakdown voltage and similar figures can be drawn for those with high breakdown voltage. Fig. 1. shows that the transformer oil breakdown voltage ROT increases with the increase of breakdown voltage. Figs. 2. and 3. show that the residual operating times of water content and total acidity decrease with the increase of their values. In general the breakdown voltage has the longest residual operating time among other characteristics such as water content and total acidity. As stated previously the increase of total acidity can be detected by the increase in transformer oil temperature. The breakdown voltage ROT is a decisive factor to indicate that all other characteristics have deteriorated and consequently to take a counter measure such as purification or replacement of transformer oils. This represents a justified conclusion from this subsection.

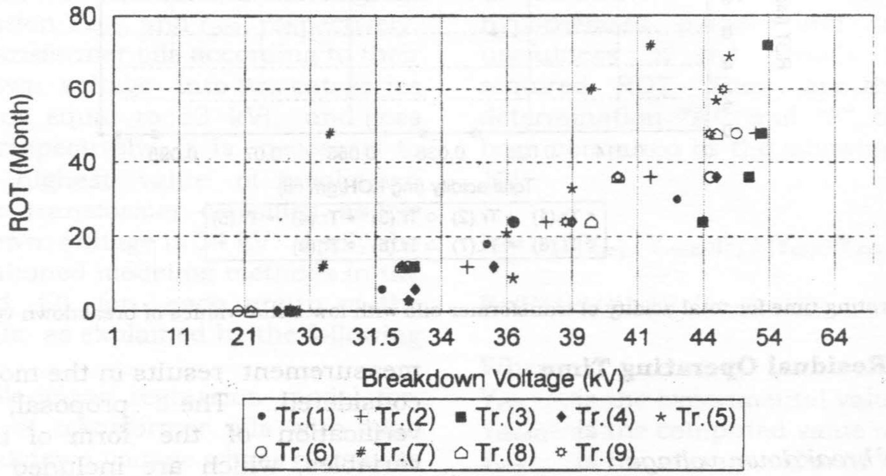

Fig. 1-a Residual-operating time for breakdown voltages of transformer oils with low initial values of breakdown voltages.

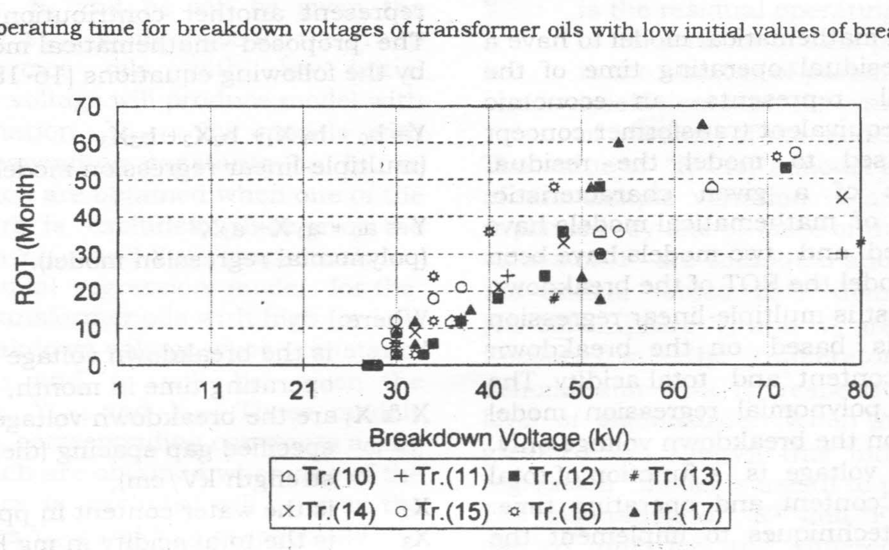

Fig. 1-b. Residual-operating time for breakdown voltages of transformer oils with high initial values of breakdown voltages.

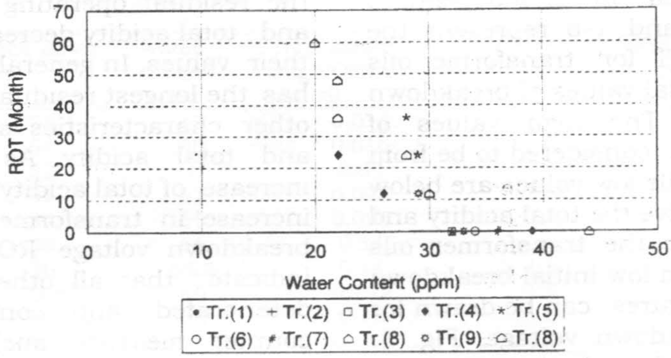

Fig. 2. Residual operating time for water content of transformer oils with low initial values of breakdown voltages.

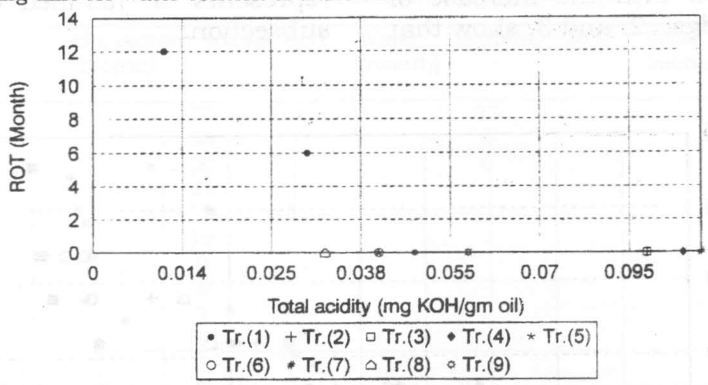

Fig. 3. Residual operating time for total acidity of transformer oils with low initial values of breakdown voltages.

4. Modeling of Residual Operating Time (ROT)

4. 1. Modeling of breakdown voltage

The use of a mathematical model to have a prediction of residual operating time of the transformer oil represents an economic necessity. The equivalent transformer concept [7] can be used to model the residual operating time of a given characteristic. Different forms of mathematical models have been investigated and two models have been proposed to model the ROT of the breakdown voltage. The first is multiple-linear regression model which is based on the breakdown voltage, water content and total acidity. The second is the polynomial regression model that is based on the breakdown voltage only. The breakdown voltage is a function of total acidity, water content and operating time. Also, different techniques to implement the measurement results in the models have been considered. The proposal, choice and verification of the form of the model and variables, which are included in the model, represent another contribution of this study. The proposed mathematical models are given by the following equations [16-18]:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3$$
(multiple-linear regression model), (1)

$$Y = a_0 + a_1 X + a_2 X^2$$
(polynomial regression model). (2)

Where:

Y is the breakdown voltage residual operating time in month,

X & X_1 are the breakdown voltage in kV for the specified gap spacing (dielectric strength kV/cm),

X_2 is the water content in ppm,

X_3 is the total acidity in mg KOH/gm oil, constants, which are required to be determined.

Applications of the proposed mathematical models are summarized in the following points:

(1) Use the experimental results of all the transformers to obtain the constants b_0, b_1, b_2 and b_3 for the multiple-linear regression (mlr) model and the constants a_0, a_1, and a_2 for the polynomial regression (pr) model. The obtained ROT of transformer oils using these constants will be given the designation Y_{mlr1} and Y_{pr1}, respectively.

(2) Exclude the results of the transformer oil whose residual operating time is required and apply the same procedure as in (1). The obtained ROT in this case will be given the designation Y_{mlr2}, and Y_{pr2}, respectively.

Divide the transformer oils according to their initial breakdown voltage into two categories (greater than or equal to 63 kV), and (less than 63 kV) respectively. It is necessary to indicate that highest value of breakdown voltage for the transformer classified as low initial breakdown voltage is 54 kV. Apply the previously mentioned modeling methods in the items (1) and (2) for each group of the transformer oils as explained by the following items.

(3) The multiple-linear regression model for the group of transformer oils with high initial breakdown voltage whose constants are b_0, b_1, b_2 and b_3 will be given the designation Y_{mlrh1} while those for the group of transformer oils with low initial breakdown voltage will produce model with the designation Y_{mlrl1}. The models with their corresponding constants b_0, b_1, b_2 and b_3 which are obtained when one of the transformers is excluded will be given the designation Y_{mlrh2} and Y_{mlrl2}, respectively.

(4) The polynomial regression model for the group of transformer oils with high (or low) initial breakdown voltage whose constants are a_0, a_1, and a_2 will be given the designation Y_{prh1} and Y_{prl1}. These models with their corresponding constants a_0, a_1, and a_2 which are obtained when one of the transformers is excluded will be given the designations Y_{prh2} and Y_{prl2}, respectively.

Methods of determination of the model constants are given in Refs. [16-18]. The percentage errors in the predicted values of transformer oil breakdown voltage ROT have been calculated by the following equation;

$$\% \text{ Error in ROT} = \{(ROT_{model} - ROT_{exp.}) / \text{Operating time (exp.)}\} \times 100 \quad (3)$$

Where:

ROT_{model} is the computed value of ROT by the model,

$ROT_{exp.}$ is the experimental value of ROT,

Operating time (exp.) is equal to ROT_{exp} at the beginning of measurements.

Two statistical quantities have been determined to assess the use of the hypothesized models and to indicate the usefulness of the models to predict the required ROT. They are the coefficient of determination "R^2" and "F" test which have been computed by the following equations [16-18]:

$$R^2 = 1 - \{\Sigma(Y_{exp.} - Y_{model})^2 / \Sigma(Y_{exp.} - Y_{avg.})^2\} \quad (4)$$

$$F = \{R^2/k\} / \{(1-R^2)/[n-(k+1)]\} \quad (5)$$

Where:

$Y_{exp.}$ is the experimental value of Y,

Y_{model} is the computed value of Y,

$Y_{avg.}$ is the average value of Y,

Y is the residual operating time,

n is the number of data points and

k is the number of parameters (coefficients of the variables or degree of freedom) of the model.

The value of "R^2" for a model implies that "R^2" of the sample variation is attributable to, or explained by one or more of the variables. The values of "F" are computed and compared with the critical values of "F" distribution $f_\alpha(\nu_1,\nu_2)$ [16-18]. Where ν_1 and ν_2 are the degree of freedom in the numerator (k) and the denominator (n-k-1) respectively and α is the level of significance. When the value of "F" is greater than $f_\alpha(\nu_1,\nu_2)$ this indicates that the regression model is useful to predict the ROT. The evaluation of "R^2" and "F" test have been carried out for the different models and modeling techniques.

4. 2 Discussion on modeling results

Tables 5, 6 and 7 show the experimental results of transformer oil breakdown voltages and the experimental and predicted residual operating times obtained by different modeling forms and techniques. These tables represent the results of transformer oils Tr. (4), Tr. (6) and Tr. (11) respectively. The following comments can be deduced from the modeling results. The transformer oils with high initial values of breakdown voltage are associated with low initial values of water content. Therefore the rapid decrease in the breakdown voltage for short subsequent intervals of time has been obtained. This has been discussed by the effect of water content in subsection 3.1. This initial rapid decrease imposes certain error in the model especially when the subsequent decrease is slow. The initial decrease in the breakdown voltage due to the increase in water content differs from one transformer to another in spite of the approximate intervals between the subsequent monitoring results. Therefore a certain deviation between experimental and modeling ROT has been obtained. This deviation decreases with the increase of operating time as the transformer oil characteristics take the course of variation of most measurement results. In polynomial regression model the same breakdown voltage values will produce the same ROT. However, in multiple-linear regression model the residual operating time decreases for the second repeated breakdown voltage. This is due to the inclusion of water content, total acidity and breakdown voltage in the model. The interdependence between these characteristics is simulated in the model and this justifies the validity of the model. Therefore it is recommended to use both models to predict ROT and depend on the smaller one to decide the countermeasure for reconditioning or replacement of transformer oils. This will give adequate and safe judgement on ROT. The application of the proposed models on the considered transformer oils revealed that the interval of six months gives to some extent an accurate estimation of ROT. The calculated percentage errors for the different models are given in Tables 5, 6 and 7. The negative sign in the final values of ROT means that violation has occurred. In Table 5 for the transformer oil which has high initial breakdown voltage values, the polynomial regression models (Y_{prh1} and Y_{prh2}) have high degree of agreement between predicted and experimental values along the course of variation of ROT with operating time. Other models such as Y_{mlrh1} and Y_{mlrh2} have fair accuracy for the last year of ROT. The error allowed in the predicted ROT depends on the importance of the transformer and its location in the network. The results given in Table 6 indicate that all models have a certain deviation in the first value of ROT. For the computed percentage error in ROT the models Y_{mlr1} and Y_{mlr2} have approximately the same error. The other models achieve zero percentage error in ROT. The models, which are obtained by considering all the transformer measurement results in the modeling, produce acceptable deviation from the experimental values for the last three years in ROT. In Table 7 the main deviation between experimental and model results appears only in the first values of ROT. This may be due to the high increase in water content as the transformer oil breakdown voltage decreased from 78 to 42 kV within a period of six months. This can be explained by the fact that purification for large number of cycles makes the transformer meticulously dry and therefore the oil will be highly affected by small amount of water. Considering the "R^2" and "F" test evaluation it can be seen that all the models passed the "F" test and the lowest value of "R^2" is 0.55 and above. This means that these models are applicable to predict ROT and the models considered variables are attributable to ROT.

Table 5 Experimental and modeling results of transformer oil Tr. (4).

BDV (kV)	Y_{exp}[1] Month	Y_{mrl1}[2] Month	Y_{mrl2}[3] Month	Y_{pr1}[4] Month	Y_{pr2}[5] Month	Y_{prh1}[6] Month	Y_{prh2}[7] Month	Y_{mlrh1}[8] Month	Y_{mlrh2}[9] Month
64	48	51.97	52.93	50.59	50.73	45.46	45.54	40.69	38.95
52	36	39.96	41.26	45.18	45.42	37.71	37.85	28.93	26.97
36	12	17.54	18.41	22.105	22.27	16.34	16.52	11.33	10.24
28	0	9.83	10.78	3.77	3.823	0.94	1.12	4.38	3.3
ROT % error	----	18.9	20.37	7.45	7.54	2.07	2.46	10.8	8.5
R^2	-----	0.563	.553	0.644	0.6373	.801	0.786	0.7412	0.7281
$F0.5$ (v_1, v_2)	-----	2.68	2.68	3.07	3.07	3.15	3.15	2.76	2.76
F_{test}	-----	49.76	46.58	105.78	100.15	110.7	95.723	52.506	44.63

$Y_{exp.}$[1]: is the experimental result.
Y_{mlr1}[2]: is the multiple-linear regression model of all transformer results.
Y_{mlr2}[3]: is the multiple-linear regression model of all transformer results except those of one of the transformers.
Y_{mlrl1}[4]: is the multiple-linear regression model of transformers with low breakdown voltages except those of one of the transformers.
Y_{mlrl2}[5]: is the multiple-linear regression model of transformers with low breakdown voltages except those of one of the transformers.
Y_{prl}[6]: is the polynomial regression model of all transformer results.
Y_{pr2}[7]: is the polynomial regression model of transformers with low breakdown voltages except those of one of the transformers.
Y_{prl1}[8]: is the polynomial regression model of transformers with low breakdown voltages.
Y_{prl2}[9]: is the polynomial regression model of transformers with low breakdown voltages except those of one of the transformer

Table 6 Experimental and modeling results of transformer oil Tr. (6).

BDV (kV)	$Y_{exp.}$[1] Month	Y_{mlr1}[2] Month	Y_{mlr2}[3] Month	Y_{pr1}[4] Month	Y_{pr2}[5] Month	Y_{prl1}[6] Month	Y_{prl2}[7] Month	Y_{mlrl1}[8] Month	Y_{mlrl2}[9] Month
49	48	36.86	36.64	42.03	42.88	52.04	52.52	53.28	54.68
45	36	32.22	32.07	37.14	37.54	44.39	45.78	44.42	45.46
36	24	21.95	21.94	21.99	21.92	25.19	26.24	24.47	24.83
32	12	17.34	17.39	13.41	13.02	15.78	15.61	15.62	15.57
20	0	5.55	5.81	-19.14	-20.87	-15.69	-23.46	-9.14	-10.4
ROT% Error		15.1	15.86	0.0	0.0	0.0	0.0	0.0	0.0
R^2	-----	0.563	0.554	0.644	0.642	0.6488	.6473	0.6735	0.6639
$F0.5$ (v_1, v_2)	-----	2.68	2.68	3.07	3.07	3.15	3.15	2.76	2.76
F_{test}	-----	49.76	46.28	105.78	101.45	55.421	49.55	39.881	34.897

Table 7 Experimental and modeling results of transformer oil Tr. (11).

BDV (kV)	Y_{exp}[1] Month	Y_{mlr1}[2] Month	Y_{mlr2}[3] Month	Y_{pr1}[4] Month	Y_{pr2}[5] Month	Y_{prh1}[6] Month	Y_{prh2}[7] Month	Y_{mlrh1}[8] Month	Y_{mlrh2}[9] Month
78	30	67.56	72.02	43.48	54.37	45.55	48.33	55.49	58.87
42	24	26.54	27.2	32.73	30.68	25.83	26.05	20.52	20.21
37	12	13.68	13.52	23.96	22.66	18.05	17.81	9.81	7.16
30	6	4.19	3.25	8.7	9.48	5.09	4.17	1.4	-2.48
21	0	-9.45	-11.31	-16.03	-10.78	-15.12	-16.99	-12.58	-1.114
ROT % error	---	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
R^2	-----	.563	.5897	0.644	.635	.801	.823	0.7412	0.785
$F0.5$ (v_1, v_2)	-----	2.68	2.68	3.07	3.07	3.15	3.15	2.76	2.76
F_{test}	-----	49.76	53.18	105.78	98.25	110.69	116.31	51.552	59.636

5. Conclusions

The conclusions inferred from this study can be summarized as follows:

(1) The standard specification violation sequence patterns of different transformer oil characteristics have been proposed and verified. The sequence of total acidity, water content and then breakdown voltage is the most common pattern.

(2) The definition of residual operating time ROT of different transformer oil characteristics has been given. The residual operating time of transformer oil breakdown voltage has proved to be descriptive for deterioration of transformer oil characteristics.

(3) Mathematical models for the residual operating time have been given. The first model is a linear regression function of transformer oil breakdown voltage, water content and total acidity. The second is a quadratic function of transformer oil breakdown voltage.

(4) Different modeling techniques have been implemented to identify model constants. The justification of applicability of the models has been verified by the prediction of experimental residual operating time.

(5) The attribution of model parameters and the dependence on it to predict the residual operating time have been approved by statistical tests.

Acknolwledg ment

The authors would like to thank the division of transformers in KIMA Company for the facilities provided during the extended period of monitoring the results. Also, the comments of the reviewers, which enhanced the clarity of the paper, are greatly appreciated.

References

[1] J. H. Provanzana, P. R. Gattens, W. H. Hagman, H. R. Moore, J. W. Harley and J. E. Triner, "Transformer condition monitoring-realizing an integrated adaptive analysis system", CIGRE Paper No. 12-105 (1992).

[2] O. Vanegas, Y. Mizuno. K. Naito and T. Kamiya, "Diagnosis of oil-insulated power apparatus by using neural network simulation", IEEE Trans. on Dielectrics and Electrical Insulation Vol. 4 (3) pp. 290-299 (1997).

[3] A. Zielonka, K. Andrzejewski and E. Gulski "Application of digital partial discharge measuring techniques for the diagnosis of high voltage generator insulation", CIGRE, International Conference on Large High Voltage Electric Systems, Paris, Paper 15/21/33-06 (1996).

[4] D. Wenzel, H. Borsi, E. Gockenbac, "Pulse shaped noise reduction and partial discharge localization on transformers using the Karhunen-Loeve-Transform", 9th International Symposium on HV Engineering, Graz, paper 5627 (1995).

[5] K. B. Cho, J. H. Park, Y. J. Kim, H. W. Ryou and T. S. Kim, "Survey and evaluation of neuro-fuzzy-logic theory to partial discharge pattern classification application",CIGRE, International Conference on Large High Voltage Electric Systems, Paris, paper 15/21/33-18 (1996).

[6] T. Kawamura, et al, "Technique of diagnosis for electrical facilities", International Electrical, Electronics of Japan and IEEJ, pp. 188-204, OUMU (1989).

[7] Mohamed A. A. Wahab, M. M. Hamada, A. G. Zeitoun and G. Ismail, "Novel modeling for the prediction of aged transformer oil characteristics", Alexandria Engineering Journal, Vol. 38 (1), pp. B11-B26 (1999).

[8] International Standard and International Electrotechanical Commission, "Method for the determination of the electric strength of insulating oil", reference number 60156, (1995).

[9] ASTM Designation D974, "Standard method of test for acidity of petroleum products", IP 139/64 (1964).

[10] International Standard and International Electrotechnical Commission, "Determination of water in insulating

liquids by coulometric automatic Karl Fisher Titration", reference number 60814 (1985).

[11] ASTM Designation D 482/85, IP4/81, "Ash from petroleum products", Standard method for analysis and testing of petroleum and related products", Book, John Wiley and Sons (1990).

[12] ASTM Designation D445-65, "Standard method of test for viscosity of transparent and opaque liquids" Adopted IP 71/66. (1960).

[13] ASTM Designation D92/7, IP36/84, Flash and Fire Points by Cleveland Open Cup", Standard Method for analysis and testing of petroleum and related products", John Wiley and Sons (1990).

[14] O. Koreh, K. Torkos, M. B. Mahara, J. Borossay and V. Izvekov: "Study of water clusters in insulating oils by Fourier transform infrared spectroscopy", IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 5 (6), December pp. 896-902 (1998).

[15] IEC publication No. 296: "Specification for new insulating oils for transformer and switchgear" (1982).

[16] R. E. Walpole and R. H. Myers: "Probability and statistics for engineers and scientists", Book, Macmillan Publishing Co., Inc, USA (1978).

[17] W. Mendenhall and T. Sincich: "Statistics for engineering and the sciences", Book, Macmillan Publishing Co., Inc., USA (1992).

[18] J. T McClave and F. H. Dietrich: "Statistics", Book, Fifth edition, Dellen Publishing, Co.USA (1991).

Received February 7, 2000
Accepted July 6, 2000