Health Monitoring of Power Transformers by Dissolved Gas Analysis using Regression Method and Study the Effect of Filtration on Oil

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***Abstract*—**Economically transformers constitute one of the largest investments in a Power system. For this reason, transformer condition assessment and management is a high priority task. If a transformer fails, it would have a significant negative impact on revenue and service reliability. Monitoring the state of health of power transformers has traditionally been carried out using laboratory Dissolved Gas Analysis (DGA) tests performed at periodic intervals on the oil sample, collected from the transformers. DGA of transformer oil is the single best indicator of a transformer's overall condition and is a universal practice today, which started somewhere in the 1960s. Failure can occur in a transformer due to different reasons. Some failures can be limited or prevented by maintenance. Oil filtration is one of the methods to remove the dissolve gases and prevent the deterioration of the oil. In this paper we analysis the DGA data by regression method and predict the gas concentration in the oil in the future. We bring about a comparative study of different traditional methods of regression and the errors generated out of their predictions. With the help of these data we can deduce the health of the transformer by finding the type of fault if it has occurred or will occur in future. Additional in this paper effect of filtration on the transformer health is highlight by calculating the probability of failure of a transformer with and without oil filtrating.

***Keywords*—**Power Transformers, Dissolve gas Analysis, Regression method, Filtration, oil.

I. Introduction

TRANSFORMERS are generally reliable and efficient equipment in a power system. There are always electrical, mechanical, thermal and environmental stresses on it and hence with the duration of time there is degradation of insulation and oil quality [1]. It leads to the occurrence of some faults that causes ultimate failure of the transformer leading to the breakdown of the power system [4]. The source of fault may lie in design, manufacturing, material used, transportation, storage, incorrect erection at site, incorrect maintenance, abnormal overload, over fluxing, lightning, external short circuit and loss of cooling. All failures cannot be avoided by preventive maintenance. Among the above mentioned causes, failures due to design error, faulty manufacturing process and lightning can not be avoided by maintenance. However maintenance can increase the transformer's ability to withstand overloads and external short circuits up to some limit. In this paper laboratory DGA tests performed at periodic intervals, on the oil samples collected from the transformers is taken as a principal method for diagnosis of fault [3]. The methods used for maintenance of transformers are costly because these, mostly involves shunting out of the transformer from the grid. To maintain the rate of power generation, another transformer of similar rating has to be powered up. While oil collection for DGA tests can be done online. With the help of dissolved gas analysis (DGA) we are able to estimate the amount of each individual unwanted gas dissolved in the transformer oil in parts per million (ppm). There are typically nine gases, namely oxygen, nitrogen, hydrogen, methane, acetylene, ethane, ethylene, carbon-dioxide and carbon-mono-oxide get generated in course of time [4,5]. The concentration of a particular gas depends on the type of fault, that is occurring. Conversely, one can say that each type of fault generate certain gases, which are popularly known as the key gases [4,5] of that particular fault. Apart from DGA, there are many more faster methods for analysis of transformer oil, available in practice. They are, spectral UV test [5], Fourier transform infrared (FT-IR) spectroscopy [6] and NMR [7]. However, all these quicker methods are very expensive and hence difficult to introduce in industrial practice. Fault occurrence in the transformer follows a random pattern. Some of the failures can be avoided and prevented for some time by periodic oil analysis and filtration, but the source of fault should finally be removed, for long term uninterrupted operation of the transformer. However analysis of oil and filtration play a key role in achieving optimum performance, reliability and longevity of the equipment. Clean oil is vital for transformer to run at optimum efficiency and minimum downtime. There are numerous options for filtering and controlling contamination level like strainers, centrifugal separators, disposal filters, cleanable filters etc [8]. The precision and amount of practical sampling is limited in case of DGA. In this paper some statistical methods have been used for the analysis of fault in transformers. Subsequently, a comparitive study has been done to evaluate the extent of correctness of different traditional methods of regression and the results are listed in table1. The measure of accuracy have been graded by comparing the numerical results with the field data obtained from DGA of oil. This prediction by regression method has been use to show the probability of the transformer failure,

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caused by different gases. Additional, in this paper, studies have been done on the behavioral characteristics of the residual gas dissolved in the oil which has undergone filtration. Through graphical means it has been clearly shown that filtration at periodic interval will extend the life of the transformer oil.

II. Study of Regression

Any method of finding a equation from a set of data is called regression. Regression equations are used for prediction purpose and judging the strenght of relations[9]. The goal in regression analysis is to create a mathematical model that can be used to predict the values of a dependent variable based upon the values of an independent variable. In other words, we use the model to predict the value of Y, which is a dependent variable when we know the value of X, a independent variable. Here correlation analysis is also used with regression analysis because correlation analysis is used to measure the strength of association between the two variables X and Y. Here traditional methods for regression like Linear, Expotential , Trigonometric and Polynomial are used, their crossponding accuracies are calculated. Some of the most frequently used methods of regression are shown below.

A. Linear Regression

In a simple linear regression for modeling *N* data points there is one independent variable: x, and two parameters, b_0 and b_1. The model can be state as follows:

$$\hat{y} = b_0 + b_1 x \tag{1}$$

$$b_0 = \frac{\sum y_k \sum (x_k^2) - \sum x_k \sum (x_k, y_k)}{nx \sum (x_k^2) - (\sum x_k)^2}$$

$$b_1 = \frac{nx(\sum y_k x_k) - \sum x_k \sum y_k}{nx \sum (x_1^2) - (\sum x_k)^2}$$

B. Exponential Regression

Exponential function is more generally used for functions of the form ab^x , where b, called the *base*, is any positive real number. Its regression model is as follows:

$$\hat{y} = ab^x \tag{2}$$

The value of a and b can be found by the method of least squares.

$$\beta = (X^T X)^{-1} (X^T Z)$$

Where β, X, Z

$$\beta = \begin{bmatrix} \ln a \\ \ln b \end{bmatrix}, X = \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ 1 & x_3 \\ . & . \\ . & . \\ 1 & x_n \end{bmatrix}, z = \begin{bmatrix} \ln y_1 \\ \ln y_2 \\ \ln y_3 \\ . \\ . \\ \ln y_n \end{bmatrix}$$

C. Polynomial Regression

One linear regression method is that of polynomial regression, which refers to finding the polynomial function that provides the least squares fitting to a series of data points. A polynomial function of degree n is given by:

$$\hat{y} = b_0 + b_1 x + b_2 x^2 + ... + b_n x^n \tag{3}$$

where $b_0 \sim b_n$ can calculated from

$$\begin{bmatrix} n & \sum x_k & ... & \sum x_k^n \\ \sum x_k & \sum x_k^2 & ... & \sum x_k^{n+1} \\ \sum x_k^2 & \sum x_k^3 & ... & \sum x_k^{n+2} \\ . & . & ... & . \\ . & . & ... & . \\ \sum x_k^n & \sum x_k^{n+1} & ... & \sum x_k^{2n} \end{bmatrix} \begin{bmatrix} b_0 \\ b_1 \\ b_2 \\ . \\ . \\ b_n \end{bmatrix} = \begin{bmatrix} \sum y_k \\ \sum x_k y_k \\ \sum x_k^2 y_k \\ . \\ . \\ \sum x_k^n y_k \end{bmatrix}$$

D. Trigonometric Regression

Another frequently used nonlinear regression method is trigonometric regression. Here the model is in terms of sinusoidal functions.

$$\hat{y} = b_0 + b_1 \sin x + b_2 \sin 2x + ... + b_n \sin nx \tag{4}$$

$b_0 \sim b_n$ can calculated from $\beta = (X^T X)^{-1} (X^T Z)$

$$\beta = \begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix}, X = \begin{bmatrix} 1 \sin x_1 & \sin 2x_1 & ... & \sin nx_1 \\ 1 \sin x_2 & \sin 2x_2 & ... & \sin nx_2 \\ 1 \sin x_3 & \sin 2x_3 & ... & \sin nx_3 \\ . & . & ... & . \\ . & . & ... & . \\ 1 \sin x_n & \sin 2x_n & ... & \sin nx_n \end{bmatrix}, z = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ . \\ . \\ y_n \end{bmatrix}$$

Error Analysis: For error analysis we compare each regression model with the original data and is stated as follow:

$$e = \sum_{k=1}^{n} e_k = \frac{1}{n} \sum_{k=1}^{n} |\hat{y}_k - y_k| \tag{5}$$

III. Simulated Results from the Field Data

To demonstrate the usefulness and effectiveness of the Regression theory, DGA data were collected from the testing laboratory, where transformer oils are sent at a regular interval. The oil samples belong to a distribution transformer having a rating of 33 KV, 5.1 MVA. Here different regression methods were applied to original field data of Ethane (C_2H_6) gas collected by DGA. The simulated results of prediction is obtained and listed in table I. The graphical representation of prediction by the regression methods are shown in Fig 1.

TABLE I SIMULATION RESULTS OBTAINED FROM DIFFERENT REGRESSION METHODS FOR ETHANE (C_2H_6) GAS (in ppm)

	y1	y2	y3	y4	y5
ORIGIN	6.0	7.5	12	21.0	29
LINEAR	3.2	9.15	15.1	21.05	27
POLY.	5.63	8.43	13.47	17.75	28.0
EXPO.	5.49	8.352	12.68	19.27	29.27
TRIG.	4.57	7.228	14.64	21.86	27.19

The errors generated from the predictions by different methods of regression are tabulated in Table II and their graphical representation is shown in Fig 2. The plot of fig 2, clearly brings out the difference in accuracy while predicting the concentration of the dissolved gas expected to be generated, by different methods. In table III we see that prediction by exponential regression incur the least error.

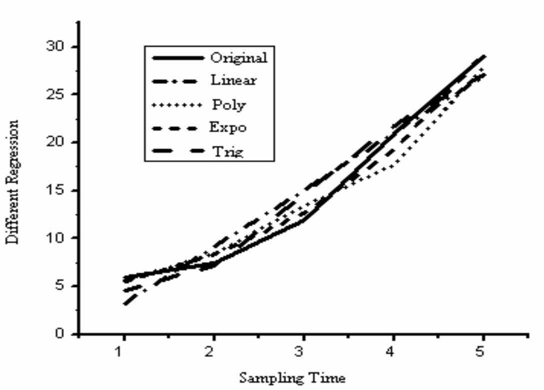

Fig. 1 Curve for different Regression methods

TABLE II ERROR ANALYSIS FROM PREDICTION BY DIFFERENT REGRESSION METHOD

	e1	e2	e3	e4	e5
Linear	2.8	1.65	3.1	0.05	2
Poly.	0.36	0.94	1.48	3.25	1.00
Expo.	0.50	0.85	0.69	1.73	0.28
Trig.	1.43	0.27	2.64	0.86	1.80

TABLE III ERROR RESULTS AND THEIR ORDER.

	LINEAR	POLY.	EXPO.	TRIG.
Error	1.92	1.405	0.80918	1.402
Order	4	3	1	2

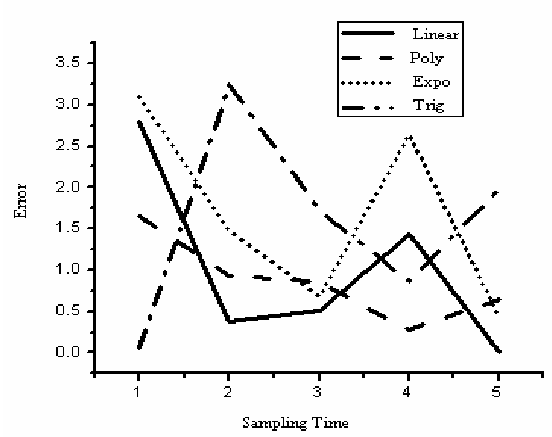

Fig. 2 Error generated from prediction by different Regression methods

IV. Filtration

As the gases are generated continuously over the period of time, accumulated quantity sometimes reaches an alarming level. Hence there is a need for a periodic oil filtering by which the dissolved gases are removed and the oil quality is refined. Existing oil filtration units for periodic oil filtrating could be classified into stationary and mobile ones [10]. The other classification is on-line (filtration process is done while machinery is working) and off-line (filtration process is done while machinery is turned–off). In an optimally designed power system most of the transformers in the distribution system are sufficiently loaded. Main disadvantage of the off-line filtration unit is the necessity of long downtime, which affects the service quality. Therefore, mobile filtration units working in on-line regime are the most preferable ones, for industrial applications, where the service engineer is able to carry the oil filtration unit to the vicinity of any particular transformer. As per the guidelines of CIGRE [2], the level of pre-failure gas concentration in the core type power transformer should lie in the range shown in table IV. Comparing the DGA data, with the values given in table IV, it may be seen, when a gas concentration is above the higher limit or likely to approach the limit shortly. Accordingly, filtration is suggested. This is the threshold limit and is used to calculate the probability of failure of the transformer. DGA data were collected from different distribution transformers having the same rating over an interval of time. In this experiment two gases (carbon mono-oxide and methane) have been chosen to see how and to what extent, these gasses affect the failure probability of a transformer. The data of these two gases were collected before and after filtration of oil and they are listed in table V and table VII respectively. Their distribution pattern is reflected in fig 3 and fig 4 respectively. It has been observed that after filtration of oil there is a remarkable change in the level of dissolved gases. By filtration mainly the carbon particles from the oil are removed, keeping the water content to a minimum. One can maintain the quality of transformer oil a long time, hence it reduces the consumption of transformer oil to a considerable extent.

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TABLE IV PRE-FAILURE GAS CONCENTRATION VALUES AT CIGRE FOR CORE-TYPE POWER TRANSFORMER.

CO	C_2H_4	C_2H_6	H_2
980-3000	700-990	750-1050	550-1320

TABLE V CONCENTRATION OF CO GAS BEFORE & AFTER FILTRATION.

Sampling time	After filtration	Before filtration
1	334.32	1221.84
2	341.02	698.41
3	369.07	1144.82
4	370.65	314.62
5	404.4	731.06
6	432.27	971.67
7	442.61	990.26
8	520.09	731.06
9	533.63	975.94

TABLE VI PROBABILITY FAILURE OF CO GAS BEFORE & AFTER FILTRATION.

Sampling no.	After filtration	Before filtration
1	0.0239	0.0873
2	0.0244	0.0499
3	0.0264	0.0818
4	0.0265	0.0225
5	0.0289	0.0522
6	0.0309	0.0694
7	0.0316	0.0707
8	0.0371	0.0522
9	0.0381	0.0697

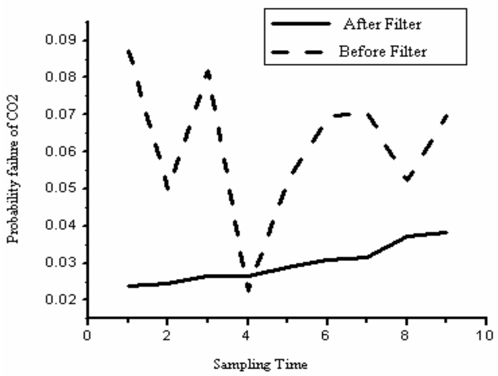

Fig. 3 Behaviour Pattern of CO Gas Before And After Filtration

Table V shows the concentration of carbon-dioxide gas in the oil before and after filtration. When the concentration of the gas approaches the limit filtration is done. The gas concentration is remarkably reduced after filtration as shown in table VI. By doing so the probability of failure of transformer is reduced. In fig 3 it is observed that after filtration the failure probability graph is fairy constant. If the oil is not filtered then the probability of failure curve would rise steeply .

V PREDICTION BY REGRESSION

Earlier we have seen that the error generated by the exponential regression method is the least, hence we apply this method for fault prediction in the transformers. For this application we will deal with only one type of gas, namely methane (CH_4). We had only eight samples as tabulated in table VII and we calculated the value of the next two samples that would be generated in the future by exponential regression. Hence the future condition of the oil could be judged. If the gas concentration was tending toward a high value then a faulty condition would be envisage and its failure probability would be high as shown in table VIII. Hence before hand remedial action can be taken. One of the remedial actions can be in the form of filtration. If faults go undetected, it is sure to cause a great damage to the health of the transformer.

TABLE VII SHOWS CH_4 GAS CONCENTRATION

Sampling time	Gas Concentration
1	0.98
2	1.73
3	2.02
4	2.54
5	2.66
6	2.12
7	1.24
8	2.44
9	2.42(exp)
10	2.56(exp)

TABLE VIII PROBABILITY FAILURE OF CH_4 GAS

Sampling no.	Gas Concentration
1	0.0075
2	0.0133
3	0.0155
4	0.0195
5	0.0205
6	0.0163
7	0.0095
8	0.0188
9	0.0186 (exp)
10	0.0197 (exp)

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VI. SERVICE PROVIDED BY FILTRATION

Filtration is the service provided in the transformer. It is a type of service, which effectively increases the life of the equipment. However, over a long period of time it can be seen that, even if the filtration is done there is always a certain amount of accumulation of gases in the oil persist and hence with time the failure probability increases as plotted in fig 4.

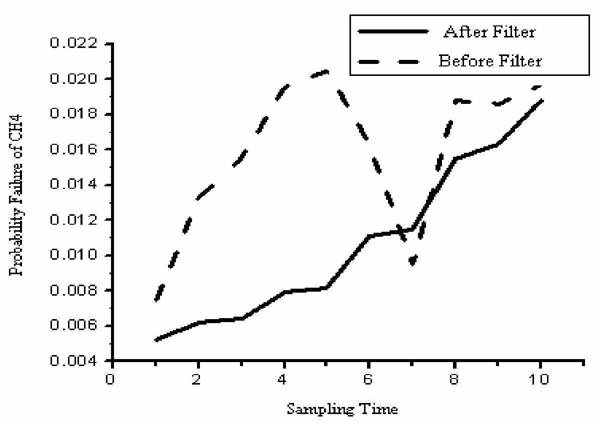

Fig. 4 Probability of Failure Increases With Time Even If Filtration is Done

TABLE IX GASES GENERATED IN OIL AND REMOVED AFTER FILTRATION.

H_2	C_2H_6	CO_2	CH_4	CO	C_2H_4	sum	Gases filtered
2002	18	2100	106	350	7	2476	
2704	49	2682	355	508	13	3616	
0.1	0.2	5	0.1	0.6	0.2	1	3615
1187	10	419	78	63	3	1338	
1462	11	530	85	64	3	1622	
0.01	0.01	82	1	2	0.01	3.02	1618.0
601	7	533	47	47	4	702	
697	14	538	50	48	2	809	
1	0.1	177	2	4	0.2	7.1	791.9
1083	68	883	112	176	10	1439	
1347	52	1179	306	431	12	2136	
7	0.01	183	1	11	0.7	19.0	2116.9

From table ix we can see even a small amount of post-filtration residual gas goes on increasing with time. The rate of gas filtered, varies as randomly as the rate of gas generation. In this part we formalize the service provided by filtration and also define some symbol.

Number of filtration (sampling rate) = N_f.
Assuming, filtration as a service provided to the system we define the total service S = 8141.97 ppm.
Mean service rate $\mu = S / N_f = 2035.49$ ppm
Total gas generated G = 8183 ppm
Hence the mean rate of gas generation $\lambda = G / N_f$
$= 2045.75$ ppm

In fig 5 $(\lambda - \mu)$ is plotted against N_f. Here one can see the rise in the residual gas over a period of time.

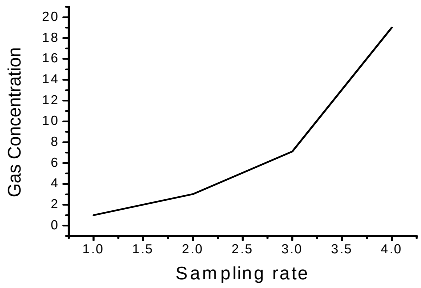

Fig. 5 Relation Between Residual Gas Concentration And Number of Filtration

VII. FAULT PREDICTION IN TRANSFORMERS.

It has been observed from table ix that the rising trend in the quantity of gases released from the insulating oil, gives us an indication of a fault that can be anticipated [11] [12]. Mainly four different faults can be detected by this method. If fault occurs, it will increase the temperature in the transformer. In this method we use an individual gas for diagnosis of fault rather than the gas ratios.

TABLE 10 FAULTS AND CORRESPONDING RESPONSIBLE GASES

	TYPE OF FAULT	PRINCIPAL GAS
1	Overheating oil	Ethylene
2	Corona in oil	Hydrogen
3	Overheated Cellulose	Carbon Monoxide
4	Arching in oil	Acetylene

In table ix, if we look at the first set of DGA data we observe that ethylene has increased nearly three fold which gives an indication of overheating in oil as shown in table 10. The second set of data gives an indication of corona in oil as the concentration of hydrogen is on the higher side. For a more accurate prediction the rising trend of these key gases has to be observed for a longer period of time without filtration or predict the volume of the gas that would be generated with the help of regression method. From the predicted value of the gas, faults could be detected.

V. CONCLUSION

In this paper we have seen that with the help of regression, we can predict the future state of a transformer, with few experimental values. It is established that exponential regression is one of the best statistical tool for prediction, compared to the other regression techniques with minimum error. This predict helps in diagnosis of fault . By filtration at a regular interval we have shown that the failure probability of the transformer decreases. The transformer should be monitored so that the mean rate of gas generation never crosses the threshold value. If the rate is high than the service rate should also increase Use of these non traditional diagnostic and monitoring techniques is expected to increase the life of the transformers. Repeated applications of these

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techniques will refine the fault prediction system to a very reliabilable statistical tool. These analitical techniques will enable the field personnels to use the test results very effectively towards the maintenance of transformers. Service engineers will be able to do the job fruitfully without depending on the human experts.

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