Performance Test of Power Transformer Prior to Maintenance using DGA and Grey Relational Analysis

Vikal R. Ingle, V. T. Ingole

Abstract— The insulation of power transformer i.e. oil and paper decomposition recognized by means of dissolved gas-in-oil analysis (DGA). To detect incipient faults in a transformer, standard key gas method of DGA is employed on the basis of quantity of gases released from the oil. This primary information also reflects the overall condition of a transformer. In this paper, condition assessment of power transformer using relative scaling is discussed. Grey relational analysis is identified as best option for relative scaling, wherein the data of fleet connected transformers is compared and accordingly scales them on the strength of score. Grey relational analysis on key gas sample determines the Target Heart Degrees (THD) of a specific transformer. However, THD represent the average estimation of bull's eye coefficients, calculated by means of attributes with equal weight condition. Subsections linearity relations are utilized to decide seven intervals for ranking purpose. Linear regression demonstrated on subsection linearity relations for different sets of key gas samples. Result shows the dominance of proposed model in deciding the maintenance priorities.

Index Terms— DGA, Key gas method, Grey Relational Analysis, Target Heart Degree, Rank Approaching Degree, subsections linearity relation.

I. INTRODUCTION

Power transformer is the main device in transmission and distribution system of any power delivery network. The reliability of transformer directly linked with the power system operations. Therefore, transformers are routinely examined to find incipient faults and avoid the potentially extended deterioration [1-4]. Special techniques are commonly adopted in monitoring the different parameters of transformer and its subsystems. Several monitoring techniques are listed as follows- *Turns ratio* provides magnetization problems and deformation of the coils. *Transformer losses* address problems like loose bus-bars, additional eddy currents and flux leakage. *Power factor test* determines the power loss of the bushing that is the quality of the capacitance. *Furan analysis* involves in *insulation* ageing process. *Partial discharges (PD)* can occur due to the presence of floating particles, cavities, or sharp points. These PD sources may be derived from their location, frequency, and charge of the occurring [5-7]. *Frequency Response Analysis* detects the mechanical deformations in transformer windings. [8]. *Infrared emission testing* useful for detecting thermal problems in a transformer. *Monitoring tap changer temperature* can be used to detect problems, such as contact overheating. *Bearing monitors* are used to detect the bearing status of oil pumps. *Hot Spot temperature* of the winding usually calculated from measurements of oil temperatures and load current. [9].*Bushing*- a major cause of failure due to Surface discharges in oil. *Winding Insulation fault* is subjected to multi-stresses. *Tap changers* – only moving element that also carries the main current, may fail due to mechanical collapse causes arcing and also erosion & decomposition of oil [10].These techniques are observed to be useful when someone looking for a specific fault in a operating transformer. A set of special measuring instruments provide the scattered result for condition assessment. Therefore, a series of combined interpretation method is needed that can establish the condition of power transformer in one assessment. However, DGA is a simple technique of faults detection and primary source to judge the condition of transformers. The worldwide accepted method, involves sampling the oil and measure the concentration of dissolved gases. The two principle causes of gas formation within an operating transformer are electrical disturbances and thermal decomposition. Most of the interpretation schemes are based on defined principles such as, gas concentrations, key gases, key gas ratios, and graphical representations.DGA Schemes such as IEC 60599, Key Gas Analysis, Roger and Doernenberg Ratio Methods, Duval triangle Method and Gas Nomograph Method. The IEEE Standard C57.104-1991 and a IEC 60599 are popularly utilizes for Interpretation [11-12]. Several studies describe the condition of the power transformer by means of the health index. These indices have been widely used as an effective indicator to evaluate the state ranking of transformer. Absolute and Relative scaling methods are preferred in transformers condition based ranking [13-14]. In absolute scaling, transformer data compared against established industry standards and relative ranking involves comparison of transformers data within the fleet. Applications of soft computing such as neural network, fuzzy logic and Adaptive Neuro-fuzzy and Genetic Algorithm etc. certainly improve the approach of analysis. However, these Model-free computing methods need significant amount of data for classifications. However, receiving the sufficient data of a transformer including all its major parameters is prohibited due to practical difficulties. Therefore, treating the distribution free small samples and inferior or uncertain information, an assessment method is needed. A system with partially known and partially unknown information is recognized as grey system. Grey system theory is useful in the condition, when less

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information about the system is available. Grey Relational Analysis (GRA) is one of the normalization methods of grey system theory and useful to solve the problems of complicated interrelationship between multiple factors and variables.

A. Key Gas Method

The prominent gases produced due to oil decompositions listed as hydrogen (H2), methane (CH4), acetylene (C2H2), ethylene (C2H4) and ethane (C2H6). Whereas, gases like carbon monoxide (CO) and carbon dioxide (CO2) develop due to paper decomposition. All these seven gases produced due to oil and paper decomposition and are referred as key gas in the literature. Faults detection by Key gas method is exercise on individual gas concentration rather than the calculation of gas ratios [11-14].

B. Grey System Theories

Prof. Julong Deng presented Grey system theory in 1980s; which is suitable for handling less data, little sample, incomplete information and devoid of experience. According to him, if the information of a system is partly known and partly unknown, it means that the system has grayness [15]. An evaluation method provides a guideline for analysis and ranking of different available alternatives for achieving certain goals or objectives. Two major categories of evaluation methods are distinguished as *Economics based methods* and *Normalization based methods* [16].

II. GRA Relational Analysis

The grey relational analysis can be used to capture the correlations among factors and contender of a system. Quantitative and qualitative relationships can be identified from numerous factors with insufficient information. The characteristics of GRA are: Need only a limited number (at least 3 values in each series) of data, the distribution of the data does not need to be explicitly considered and it provides a simple calculation procedure [16]. The procedure of GRA is to first translate the performance of all alternatives into comparability sequence. An ideal reference sequence is defined according to these sequences. The grey relational coefficient between all comparability sequences and reference sequence is calculated. On the basis of these grey relational coefficients, the grey relational grade between the reference sequence and every comparability sequence is calculated [17]. The algorithm [18-21] briefly summarized below-

Constructing standard pattern (bull's eye)

Assume ωi is the state model-i, ω(k) is the state parameter sequence-k for one certain equipment, Constructing the

- ***Standard state model- ω0:***

Assume ωi is the multi-polarity criteria sequence:
ωi = { ωi(1), ωi(2),…………,ωi(n)}
∀ ωi (k) Є ωi => k Є K={1,2,...,n},
i Є I={1,2,..,m}
Define ω(k) as specification model sequence:
ω(k)=(ω1(k), ω2(k),..., ωm(k))
∀ ωi (k) Є => ω(k) => i Є I={1,2,..,m}
Suppose POL (max), POL (min), POL (mem) refers to the maximum polarity, the minimum polarity and the medium polarity respectively.

i) While POL ωi(*k*) = POL(max), then ω0(k) = maxi ωi(k), ωi(k) Є ω(k)
ii) While POL ωi(*k*) = POL(min), then ω0(k) = mini ωi(k), ωi(k) Є ω(k)
iii) While POL ωi(*k*) = POL(mem), then ω0(k) = avgi ωi(k), ωi(k) Є ω(k)
and the standard pattern sequence will be-
ω0 = { ω0(1), ω0(2),..., ω0(n)} also called as target heart.

- ***Transforming grey target***

Assume that T is a grey target transform, then

$$Twi(k) = \frac{\min\{Wi(K), Wo(k)\}}{\max\{\{Wi(K), Wo(k)\}} \quad \dots\dots..(1)$$

Where, X0 refers to the standard bull‟s eye and X0(k) Є X0
=> X0 = Tω0
and, Tω0 = X0 = (1, 1………….. 1)

- ***Calculate grey bull's eye coefficients and Target heart degree***

The coefficient of target heart degree calculate through

$$\gamma\big(x0(k), xi(k)\big) = \frac{\{\min_i \max_k \Delta oi(k) + \rho \max_i \max_k \Delta oi(k)\}}{\Delta oi(k) + \rho \max_i \max_k \Delta oi(k)} \quad \dots. (2)$$

ρ‟ is the resolving coefficient, ρ Є [0,1] , generally ρ= 0.5 ; Δoi (k) shows the grey relational different information space between evaluated sequence ωi and target heart ω0**.**
ΔOi (k) = | X0(k) – Xi (k) | = | 1- Xi (k) | ;
ΔOi (min) = $min_i \, min_k$min.Δo_{ik} ;
ΔOi (max) = $max_i \, max_k$min.Δo_{ik} ;
Taking the average of the grey relation coefficient to Target heart degree by applying –

$$\gamma\,(x_0,x_i) = \frac{1}{n}\sum_{k=1}^{n}\gamma\big(x0(k), xi(k)\big) \quad \dots\dots (3)$$

- **Rank approaching degree**

The approaching degree will rank the alternatives into nine interval levels as follows: [0.9, 1.0]; [0.8, 0.9]; [0.7, 0.8]; [0.6, 0.7]; [0.5, 0.6]; [0.4, 0.5]; [0.3, 0.4]; [0.2, 0.3]; [0.1, 0.2]. Suppose equal weights are considered for every attributes then ρ = 0.5, and

$$\gamma\,(x_0,x_i) \geq \frac{\rho}{\rho+1} = 0.3333 \quad \dots\dots (4)$$

Based on above basic principle, the pros degree of each alternative separated as: [0.9, 1.0] ; [0.8, 0.9] ; [0.7, 0.8] ; [0.6, 0.7] ; [0.5, 0.6] ; [0.4, 0.5] ; [0.33333, 0.4] . Therefore, equal weight criteria set the seven intervals ranges from 0.3333 to 1.

III. Calculation of Target Heart Degree

The grey relational analysis performs on DGA samples to determine the Target Heart Degree of every transformer. The minimum polarity criterion is chosen for concentration values of every gas. As the lowest amounts of gas concentration indicates the better health of transformer. The samples are normalized by means of equation (1).The grey relational different information space between evaluated sequence and standard bull's eye is calculated, to get the coefficients of target heart degree through equation (2).The equal weights are considered for every key gas though every key gas is equally important in transformer's condition judgment and hence applied the resolving coefficient as 0.5 i.e. (ρ= 0.5). The averages of the grey relational coefficients are calculated using equation (3) and find target heart degree of a specific sample. It is observed that, in grey relational analysis, all specimens are relatively ranked in the interval from 0.3333 to 1. The results are displayed in Table-1.

Table1: Sequence of state specification and equivalent Target Heart Degree

Specification	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	THD
ω_1	10.44	8.62	4.63	6.84	0.16	0.617
ω_2	138.1	140.2	137.8	142.6	0.4	0.341
ω_3	132.49	824	349.5	683.2	2.19	0.338
ω_4	275.5	832.4	355.9	1208.3	22.85	0.335
ω_5	353.3	44.7	22.7	16.4	15.13	0.357
ω_6	477.4	409.8	245.2	1231	110.53	0.335
ω_7	261.1	699.6	196.5	1055.1	322.6	0.336
ω_8	41.48	4.49	3.83	3.19	0.01	0.880

IV. Assessment of Subsection Linearity Relations

The use of grey relational analysis provides the relative rank of all specimens in the form of THD. The score is estimated for different values of THD to set the grade and state of every transformer. This necessitates the corresponding intervals or boundaries for classification. The relationship between THD and classification intervals are linked by means of subsection linearity relations. This supports in categorizing the testing transformers to fix the maintenance priority. In this section two string of subsection linearity relations are examined between THD and estimation of score on simple regression. The four subsection linearity relations and ranking structure of Ref. [11] is shown in Table-2, which is employed to find the score of test samples.

Table 2: Subsection Linearity Relations for State and Score ranking

Subsection Linearity Relations	Target Heart Degree	State	Score	Grade
150γ -50	$\gamma \in [0.9,1]$	Healthy	[85-100]	I
83.33γ -10	$\gamma \in [0.6,0.9)$	Normal	[60-85)	II
200γ -60	$\gamma \in [0.5,0.6)$	Slight Fault	[40-60)	III
200γ -60	$\gamma \in [0.4,0.5)$	Middle Fault	[20-40)	IV
285.7γ - 94.29	$\gamma \in [0.33,0.4)$	Serious Fault	[0-20)	V

The proposed subsection linearity relations are established through seven rank approaching intervals. The structure of the same displayed in Table-3.

Table 3: Proposed Subsection Linearity Relations for Relative Ranking

Subsection Linearity Relations	Target Heart Degree	State	Score	Grade
S= 100 γ	$\gamma \in [0.9,1]$	Healthy	[90-100]	I
S= 150 $\gamma - 45$	$\gamma \in [0.8,0.9)$	Absolute Normal	[75-90)	II
	$\gamma \in [0.7,0.8)$	Normal	[60-75)	III
	$\gamma \in [0.6,0.7)$	Slight Fault	[45-60)	IV
	$\gamma \in [0.5,0.6)$	Middle Fault	[30-45)	V
	$\gamma \in [0.4\text{-}0.5)$	Serious Fault	[15-30)	VI
S≈ 214.29γ − 70.71	$\gamma \in [0.33\text{-}0.4)$	Critical	[0-15)	VII

The linearity relations [11] are first consider on the complete range of THD (from 0.3333 to 1) with sample size of 34 and five classification levels. The line of best fit has given the regression equation as Y1 = 133.57*X1 - 29.79 on 0.9546 coefficients of determination. The range of score detect from min (-0.0057) to max (100). However, the proposed three subsection linearity relations shown 0.9978 coefficients of determination with regression equation of Y2 = 149.37*X2 - 45.27 on line of best fit. The score calculation range varies from min (+ 0.0057) to max (100) using proposed relations. Both the regression equations are further applied to estimate the score of eight specimens [11] and error of estimation results are shown in Table-4. It is observed that the precision of estimation can be obtained only through a measure of the magnitude of error called error of estimation. This means that the estimation values of one variable based on the known values of the other variable are always bound to differ. Therefore, the smaller differences of estimation produce higher precision in predictions. These relations are further confirmed on other new samples of DGA. The calculated THD of new DGA samples are shown in Table-5.

Table 4: Error Estimation of Two subsection linearity

THD	Yo	Y_1=133.57X_1-29.79	Error of Estimation
0.6170	1.5942	15.037	11.5268
0.3417	1.6799	15.0761	
0.3381	1.8228	15.1429	
0.3359	2.3085	15.37	
0.3578	3.3371	15.8508	
0.3356	7.937	18.0013	
0.3364	61.4146	52.6226	
0.8801	83.3395	87.7663	
THD	Yo	Y_2=149.37X_1-45.27	Error of Estimation
0.6170	1.2057	4.8585	2.92201
0.3417	1.27	4.9033	
0.3381	1.3771	4.978	
0.3359	1.7414	5.2319	

0.3578	2.5129	5.7697	
0.3356	5.9629	8.1745	
0.3364	47.55	46.8913	
0.8801	87.0165	86.192	

Table 5: Calculated THD of Key gas Samples

Spn.	H_2	CH_4	CO	CO_2	C_2H_4	C_2H_6	C_2H_2	**THD**
1	53	49.2	748	6021	2824	514	31	0.337
2	12	325	11.8	787	0.01	2.9	108.5	0.549
3	0.01	2.2	33.6	322	0.7	0.6	0.01	0.810
4	0.01	19.3	140	1879	0.01	57.2	0.01	0.632
5	18.9	303	432	3114	0.01	157	0.8	0.433
6	0.01	46.3	219.2	9909	6.02	16.4	0.01	0.529
7	0.01	2.08	33.7	327	0.7	0.6	0.01	0.820
8	0.01	18.8	159	3303	47	60	0.01	0.533
9	12	8778	317	2959	11900	4834	18.7	0.338
10	0.01	73.4	123.7	66260	0.01	88.2	0.01	0.623

Spn-Specimen

The proposed model has effectively given the minimum error of estimation (1.6823) as compared to (7.5995) contender. The linear relationship implies the constant change in the dependent variable with respect to changes in the independent variables and hence extensively exercised for prediction.

V. CONCLUSION

DGA based assessment exercise using grey relational analysis reflects the relative ranking of the transformers connected in a fleet. The linear regression between THD and estimation score is useful in targeting the state and grades of transformers. The standard error of estimate measures the dispersion around the regression line and line of best fit. The proposed model based on new subsection linearity relations have shown certain degree of improvement and successfully ranked the transformer within seven grades, so as to plan maintenance of an entity. This ranking Policy will certainly helps in setting the priorities about investment and maintenance of transformers.

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