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An Empirical Study on Degrees of Grey Incidences to Decide Maintenance Priorities of Power Transformers

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***Abstract*— Dissolved gas analysis (DGA) is a vital and secure technique to judge the condition of power transformer at early stage. The caution levels of gases specified in different standards of DGA referred while deciding the maintenance policy. In this article, degrees of grey incidences are introduces which deals in distribution free small samples. The test samples of DGA considered as behavioural sequences and three caution levels as system characteristics. The metric space consists of system factors and gray incidence operators forms a base for investigation. The complex interrelationship is determined through absolute degree, relative degree and synthetic degree of grey incidences. An empirical procedure finds the synthetic degree of grey incidence in terms of numerical index which helps in ranking and assists in setting the priorities about maintenance of transformers.**

***Index Terms*— DGA, Key gas caution levels, Grey System Theory, metric space, degrees of grey incidences.**

I. Introduction

Power Transformer is the most significant as well as expensive equipment in the power network. Paper and oil insulations degraded because of thermal, electrical, chemical and mechanical stresses during power delivery [1]. The major dissolved gases- in- oil exist hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), ethane (C_2H_6), carbon monoxide (CO) and carbon dioxide (CO_2). All these seven gases referred as 'key gases' in the literature [2]. Dissolved gas analysis is worldwide accepted technique based on which incipient faults and health of the power transformer is detected. The DGA method includes key gas and ratio methods [3]. The expert system [4] with smart sensors added precision in DGA interpretation. The soft computing techniques such as neural network [5], fuzzy logic and Adaptive Neuro-fuzzy [6-10] and Genetic algorithm [11] are widely applicable in dissolved gas analysis. However, these Model-free computing methods need significant amount of data for classifications.

A. Condition Based Ranking of Transformer:

A guide published the standard IEEE C.57.104™ classify the risk of transformer into three levels. It also provides transformer maintenance warning depends on the quantities of total dissolved combustible gases i.e. TDCG in the oil [2]. A comprehensive proposal of Weidmann-ACTI has developed a rigorous method for condition appraisal of power transformers. An overall condition ranking performed on the assigned weights of different components. The transformers thereafter rank from worst (level-1) to best (level-15) condition. In this report, main tank oil DGA has given significant weights [12]. Toronto Hydro-Electric group uses

Condition Parameter Factors (CPF) for oil quality and DGA to judge transformer ranking [13]. Several studies describe the state of the power transformer using health index [14-15]. Absolute and Relative scaling methods are generally used in transformers condition based ranking. In absolute scaling transformer data compared against established industry standards, whereas relative ranking involves comparison of data within the fleet of transformers**.**

II. GREY SYSTEM THEORY

The partially known scheme is said to be a grey system. Prof. Julong Deng presented the Grey system theory in 1980s, which is an extension of fuzzy set theory [16] and useful to study grey systems. This theory is suitable for distribution free small sample sizes and appropriate to tap the inferior and uncertain information. Grey numbers, grey elements and grey relations are the main subjects of research in grey system theory. Recently, some researchers have applied grey relational analysis for multi-criteria vague decision making i.e. MCVD [17-18].

A. *Grey Incidence Analysis:*

Grey incidence analysis is one of the elements of grey system theory in which the system performance is tested on absolute, relative and synthetic degrees of grey incidences. All these atypical degrees of grey incidences are numerical characteristics for the relationship of closeness between two sequences. When analysing a relationship between system's characteristic behaviours and relevant factors, then the magnitudes of degree of incidences relatively order all the elements and factors. The relevant degree of grey incidence can be defined by using the distance function in the n-dimensional space [19]. The matrices of grey incidences are used for desirable classifications. The cluster of grey incidences mainly used to classify factors of the same type, in order to simplify the complicated systems or phenomenon.

B. *Factors and degrees of Grey Incidences*

The characteristics of the system signified through mapping the quantities and factors of it. If quantitative analysis is needed then process of mapping is perform through sequence operators. This resulted into non-dimensional sequences of identical behaviour of the system for negatively correlated and positively correlated factors [19].

Definition 1: Assume that Xi is a systems' factor with the K^{th} observation value being $Xi(k)$, *k =1, 2....., n.*

$$Xi = [Xi(1), Xi(2), \dots\dots\dots\dots, Xi(n)]$$

is called a behavioural sequence of the factor Xi .

Definition 2: Sequence operator for K^{th} observation value

$$Xi(k)D1 = [Xi(1)\ d1, Xi(2)\ d1, \dots\dots\dots, Xi(n)\ d1]$$

$$Xi(k)d1 = \frac{Xi(k)}{Xi(1)}$$

For *k =1, 2,.......,n.* Then D_1 is called an initializing operator with Xi as its pre-image and $Xi(k)D1$ as its image, called the initial image of Xi.

Definition 3: Let Xi be the same as in definition 1

$$Xi = [Xi(1), Xi(2), \dots\dots\dots\dots, Xi(n)]$$

and D a sequence operator- $Xi(k)D = [Xi(1)\ d, Xi(2)\ d, \dots\dots\dots, Xi(n)\ d]$

$$Xi(k)d = [Xi(k) - Xi(1)]$$

Then D is called a zero starting point operator with XiD as its image of zero starting point of Xi denoted as

$$x_i^0 = [x_i^0(1)\,,\, x_i^0(2)\,, \ldots\ldots\ldots\, x_i^0(n)]$$

Definition 4: Assume that $\mathcal{X}i$ and $\mathcal{X}j$ are one interval sequences of the same length, and denoted as

$$x_i^0 = [x_i^0(1)\,,\, x_i^0(2)\,, \ldots\ldots\ldots\, x_i^0(n)]\,; \qquad x_j^0 = [x_j^0(1)\,,\, x_j^0(2)\,, \ldots\ldots\ldots\, x_j^0(n)]$$

Then the zero images of $\mathcal{X}i$ and $\mathcal{X}j$ are-

$$|S_i| = \left| \sum_{k=2}^{n-1} x_i^0(k) + \frac{1}{2} x_i^0(\mathbf{n}) \right|$$

$$|Sj| = \left| \sum_{k=2}^{n-1} x_j^0(k) + \frac{1}{2} x_j^0(n) \right|$$

and

$$|Si - Sj| = \left| \sum_{k=2}^{n-1} [x_i^0(k) - x_j^0(k)] + \frac{1}{2} [x_i^0(n) - x_j^0(n)] \right|$$

Definition 5: Assume that two sequences $\mathcal{X}i$ and $\mathcal{X}j$ are one interval sequences of the same length, and s_i and sj are defined in definition 4 then

$$\varepsilon ij = \frac{1 + |si| + |sj|}{1 + |si| + |sj| + |si - sj|}$$

is called ***absolute degree of grey incidence*** of $\mathcal{X}i$ and $\mathcal{X}j$, which satisfies the property of normality i.e. $\varepsilon ij > 0$ and $|si - sj| > 0,$ sothat $\varepsilon ij \leq 1$, pair symmetry expressed as $|si - sj| = |sj - si|$ and closeness. Whereas , $0 < \varepsilon ij < 1$ and εij is only related to the geometrical shapes of $\mathcal{X}i$ and $\mathcal{X}j$ (not with spatial position) and has no effect moving horizontally. When one of the data value or length of sequence changes εij also changes accordingly.

Definition 6: Assume that $\mathcal{X}i$ and $\mathcal{X}j$ are two sequences of the same length with the initial values being zero, $\mathcal{X}i'$ and $\mathcal{X}j'$ are the initial image of $\mathcal{X}i$ and $\mathcal{X}j$ respectively. Then, the absolute degree of grey incidence of $\mathcal{X}i'$ and $\mathcal{X}j'$ is called the ***relative degree of grey incidence***, denoted as $\boldsymbol{r_{ij}}$ and $0 < \boldsymbol{r_{ij}} < 1$. The concept of relative degree of grey incidences of sequences $\mathcal{X}i$ and $\mathcal{X}j$ is quantitative representation of the rate of change of $\mathcal{X}i$ and $\mathcal{X}j$ relative to their starting point. The closer the rates of change of $\mathcal{X}i$ and $\mathcal{X}j$ are the greater r_{ij} is, and vice versa.

Definition 7: When overall relationship of closeness between sequences is considered, then assumes that $\mathcal{X}i$ and $\mathcal{X}j$ are two sequences of the same length with non-zero initial entries, that εij and r_{ij} are the absolute degree and relative degree of grey incidence of $\mathcal{X}i$ and $\mathcal{X}j$, and $\theta \in [0,1]$.Then it is called

$$\rho_{ij} = \boldsymbol{\theta\, \varepsilon ij} + (1 - \boldsymbol{\theta})\ \boldsymbol{r_{ij}}$$

as ***Synthetic degree of grey incidences between*** $\mathcal{X}i$ and $\mathcal{X}j$.

In general, we can take $\theta = 0.5$ but if we are more interested in the relationship between some absolute quantities, then greater value can be used. If putting more emphasis on rate of change, smaller value can be employed for θ . ρ_{ij} is related to each observation value in the sequences $\mathcal{X}i$ and $\mathcal{X}j$ and also the rate of change of each data value w.r.t. initial point. It has following major properties- never equals to zero but $0 < \rho_{ij} < 1$. When $\theta = 1$, then $\rho_{ij} = \boldsymbol{\varepsilon ij}$ and when $\theta = 0$ then $\rho_{ij} = \boldsymbol{r_{ij}}$.

Definition 8: If there exist a $K \in \{1,2, \ldots\ldots, s\}$ | for any, *i =1,2,....... ,s*, then $Y_k \gg Y_i$ and Y_k is called quasi-preferred characteristic of the system.

Definition 9: If a system with ***s*** characteristic and the ***m*** relevant factors such that, $l \in \{1,2, \ldots\ldots, m\}$ and *j=1,2,....... ,m*, then factor X_l is said to be a quasi-preferred factor.

Definition 10: There may not be the most favourable System characteristics ***(s)*** and the factors ***(m)*** but there must be quasi-preferred characteristic and factors. The concept of synthetic degree of grey incidence is a numerical index which describes the overall relationship of closeness between sequences [19].

III. DEGREES OF GREY INCIDENCES FOR TRANSFORMERS RANKING

DGA sample of seven key gases indicates the conditions of oil and paper decomposition. The insulation strength also reflects the status of transformers through which one can rank them for maintenance.

A. Threshold Levels of Key gases:

International regulations IEC, IEEE, CIGRE, MSZ National standard's ratio codes and graphical techniques are widely employed by utilities. These standards provide guidance of threshold limits for investigation, analysis and applications [1-3]. The IEEE std.C.57.104 specified three threshold levels (as shown in Table -I) are used as sequences of system's characteristic behaviours. The five gas samples (shown in Table-II) are tested through degrees of grey incidences.

Table I. IEEE std.C.57.104

Key Gases	System Characteristics		
	Y1	Y2	Y3
H_2	100	700	1800
CH_4	120	400	1000
CO	350	570	1400
CO_2	2500	4000	10000
C_2H_4	50	100	200
C_2H_6	65	100	150
C_2H_2	35	50	80

Table II: DGA gas Samples

Key Gases	System behavioral Sequences				
	X1	X2	X3	X4	X5
H_2	53	12	1	12	1
CH_4	49	325	19	8778	73
CO	748	12	140	317	124
CO_2	6021	787	1879	2959	66260
C_2H_4	2824	1	1	11900	1
C_2H_6	514	3	57	4834	88
C_2H_2	31	108	1	18	1

B. Degree of grey Incidences:

The metric space consists of system factors and gray incidence operators which forms a base for analysis. The procedure of ranking is performed on absolute, relative and synthetic matrix of grey incidences respectively.

C. Absolute Matrix of Grey Incidence:

Considering the IEEE specified (Table-I) caution levels as system characteristics (***s***) and the relevant key gas concentrations (Table-II) as system factors ***(m).***The image of zero staring point is computed using all these sequences. Thereafter, System factors are evaluated with every system characteristics to find the coefficients of absolute degree of grey incidences. The Absolute matrix of Incidences estimation is as follows-

$$A=[\varepsilon ij]_{3\times 5} = \begin{pmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} & \varepsilon_{14} & \varepsilon_{15} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} & \varepsilon_{24} & \varepsilon_{25} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} & \varepsilon_{34} & \varepsilon_{35} \end{pmatrix} = \begin{pmatrix} 0.6292 & 0.7187 & 0.9096 & 0.5444 & 0.5192 \\ 0.5681 & 0.9149 & 0.8217 & 0.5234 & 0.5101 \\ 0.6463 & 0.6931 & 0.8618 & 0.5503 & 0.5217 \end{pmatrix}$$

From the absolute matrix of incidence, let us consider

$$\sum_{j=1}^{5} \varepsilon_{1j} = 3.3211 \qquad \sum_{j=1}^{5} \varepsilon_{2j} = 3.3382 \qquad \sum_{j=1}^{5} \varepsilon_{3j} = 3.2732$$

The rows of A satisfy $\mathbf{Y_2 \geq Y_1 \geq Y_3}$

i.e. Y_2 is the most quasi- preferred characteristic, Y_1 the second and Y_3 the last. All columns of A gives

$$\sum_{i=1}^{3} \varepsilon_{i1} = 1.8436 \qquad \sum_{i=1}^{3} \varepsilon_{i2} = 2.3267 \qquad \sum_{i=1}^{3} \varepsilon_{i3} = 2.5931$$

$\sum_{i=1}^{3} \varepsilon_{i4}$ = 1.6181 $\sum_{i=1}^{3} \varepsilon_{i5}$ = 1.551

$$\mathbf{X_3 \geq X_2 \geq X_1 \geq X_4 \geq X_5}$$

Hence, X_3 is the most quasi-preferred transformer, X_2 the second, X_1 the third, X_4 the fourth and X_5 the last.

D. Relative Matrix of Grey Incidence:

In relative degree of incidences, the initial images of system characteristic and relevant factors are obtained as per the definition 2. Then the images of zero starting points of all sequences are generated to calculate the coefficients of relative degree of grey incidences. The Relative matrix of Incidences is,

$$B = [r_{ij}]_{3x3} = \begin{pmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} \end{pmatrix} = \begin{pmatrix} 0.5696 & 0.6392 & 0.5062 & 0.5054 & 0.5002 \\ 0.5065 & 0.5129 & 0.5006 & 0.5005 & 0.5000 \\ 0.5056 & 0.5113 & 0.5005 & 0.5004 & 0.5000 \end{pmatrix}$$

From the relative matrix of incidence, consider

$\sum_{j=1}^{5} r_{1j}$ = 2.7206 $\sum_{j=1}^{5} r_{2j}$ = 2.5205 $\sum_{j=1}^{5} r_{3j}$ = 2.5178

The rows of B give the system characteristic as,

$$\mathbf{Y_1 \geq Y_2 \geq Y_3}$$

i.e. Y_1 is the most quasi- favourable characteristic, Y_2 the second and Y_3 the last, and from columns -

$\sum_{i=1}^{3} r_{i1}$ = 1.5817 $\sum_{i=1}^{3} r_{i2}$ = 1.6634 $\sum_{i=1}^{3} r_{i3}$ = 1.5073

$\sum_{i=1}^{3} r_{i4}$ = 1.5063 $\sum_{i=1}^{3} r_{i5}$ = 1.5002

$$\mathbf{X_2 \geq X_1 \geq X_3 \geq X_4 \geq X_5}$$

X_2 is the mainly quasi- preferred transformer, X_1 the second, X_3 the third, X_4 the fourth and X_5 the last.

E. Synthetic Matrix of grey Incidence:

This degrees of grey incidence find the overall relationship of closeness between the two sequences by making the use of relation given in definition 7.Selecting the resolving factor i.e. $\theta = 0.5$ coefficients of synthetic degrees are find and matrix is formed as below. The Synthetic matrix of Incidences,

$$C = [\rho ij]_{3\times5} = \begin{pmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} & \rho_{15} \\ \rho_{21} & \rho_{22} & \rho_{23} & \rho_{24} & \rho_{25} \\ \rho_{31} & \rho_{32} & \rho_{33} & \rho_{34} & \rho_{35} \end{pmatrix} = \begin{pmatrix} 0.5994 & 0.6790 & 0.7079 & 0.5249 & 0.5097 \\ 0.5373 & 0.7139 & 0.6612 & 0.5120 & 0.5051 \\ 0.5760 & 0.6022 & 0.6812 & 0.5254 & 0.5109 \end{pmatrix}$$

The entries from the matrix C given as,

$\sum_{j=1}^{5} \rho_{1j}$ = 3.0209 $\sum_{j=1}^{5} \rho_{2j}$ = 2.9294 $\sum_{j=1}^{5} \rho_{3j}$ = 2.8955

from the rows of C, $\mathbf{Y_1 \geq Y_2 \geq Y_3}$

and from columns,

$\sum_{i=1}^{3} \rho_{i1}$ = 1.7127 $\sum_{i=1}^{3} \rho_{i2}$ = 1.9951 $\sum_{i=1}^{3} \rho_{i3}$ = 2.0502

$\sum_{i=1}^{3} \rho_{i4}$ = 1.5622 $\sum_{i=1}^{3} \rho_{i5}$ = 1.5592

$$\mathbf{X}_3 \geq \mathbf{X}_2 \geq \mathbf{X}_1 \geq \mathbf{X}_4 \geq \mathbf{X}_5$$

System characteristic point of view Y_1 is the quasi- preferred characteristic, Y_2 the second and Y_3 the last. Therefore, X_3 is the quasi- preferred transformer, X_2 the second, X_1 the third, X_4 the fourth and X_5 the last. All the different degrees of grey incidences has numerical uniqueness and applicable in finding the closeness of relationship between the sequences. The absolute order of incidences seems at the relationship from angle of absolute magnitudes and in relative order of incidences angle of rate of change is observed. The result from synthetic order of incidences combined the angle of absolute magnitudes and rate of change.

IV. ABSOLUTE ORDER OF INCIDENCES

When the behavioural sequence and the relevant factors are consider on a specified operator of grey incidences. Subsequently, it is enough to consider the higher values of θ to get the absolute order of incidences. Therefore, the value of θ varies from 0.5 to 0.9 as the θ =1, resulted into absolute degree of grey incidence. The confirmation of the same is shown in Table-III. The result indicates that the transformer no. 4 & 5 are in critical conditions refer to all levels of system characteristics. It is observed that ranking of transformer no.3 attained higher rating followed by transformer no.2. However, transformer no.1 gained the moderate position. The system characteristic point of view Y_1 attained the higher rank in quasi- preferred situation.

Table III: Specified operators and Grey incidences

θ	ρ_{i1}	ρ_{i2}	ρ_{i3}	ρ_{i4}	ρ_{i5}	Σ Row
Θ = 0.5	0.5994	0.6790	0.7079	0.5249	0.5097	**3.0209**
	0.5373	0.7139	0.6612	0.5120	0.5051	**2.9295**
	0.5760	0.6022	0.6812	0.5254	0.5109	**2.8957**
Σ Column	**1.7127**	**1.9951**	**2.0503**	**1.5623**	**1.5257**	--------
Θ = 0.6	0.6054	0.6869	0.7482	0.5288	0.5116	**3.0809**
	0.5435	0.7541	0.6933	0.5142	0.5061	**3.0112**
	0.5900	0.6204	0.7173	0.5303	0.5130	**2.9710**
Σ Column	**1.7389**	**2.0614**	**2.1588**	**1.5733**	**1.5307**	--------
Θ = 0.7	0.6113	0.6949	0.7886	0.5327	0.5135	**3.1410**
	0.5496	0.7943	0.7254	0.5165	0.5071	**3.0929**
	0.6041	0.6386	0.7535	0.5353	0.5152	**3.4266**
Σ Column	**1.7650**	**2.1278**	**2.2674**	**1.5845**	**1.5358**	--------
Θ = 0.8	0.6173	0.7028	0.8289	0.5366	0.5154	**3.2010**
	0.5558	0.8345	0.7575	0.5188	0.5081	**3.1747**
	0.6182	0.6567	0.7895	0.5403	0.5174	**3.1221**
Σ Column	**1.7913**	**2.1940**	**2.3759**	**1.5957**	**1.5409**	--------
Θ = 0.9	0.6232	0.7108	0.8693	0.5405	0.5173	**3.2611**
	0.5629	0.8747	0.7896	0.5211	0.5091	**3.2564**
	0.6322	0.6749	0.8257	0.5453	0.5195	**3.1976**
Σ Column	**1.8173**	**2.2604**	**2.4845**	**1.6069**	**1.5459**	--------

CONCLUSION

This paper introduced the alternative method for system analysis .The pitfalls of statistical methods are overcome in the Grey incidence analysis. This theory successfully exercised on DGA sample which reflects the integrated sequence of interaction and the impact of typical gases on particular transformer. The use of metric spaces showed certain degree of success in the classifications. The results from synthetic degrees of grey incidences are useful in analysing the systems and helps in setting the priorities of transformers about maintenance.

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