Absolute and Relative Scaling of Power Transformers using Grey Incidence and Relational Analysis

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ABSTRACT

Health or criticality index of power transformer is computed by utilizing the heuristic knowledge, employed on massive parametric data. For assessment purpose, it is unreasonable to collect the huge data of monitoring and test equipments frequently. As a first information source, dissolved gases-in-oil is secured in interpreting the transformer condition. The major seven dissolved gases are referred as key gases in IEEE/IEC gas guide. Dissolved Combustible Gases (TDCG) standard for state assessment uses caution levels of key gases for condition judgment. The phenomenon of dissolved-gas-in-oil observed analogous to grey system, as one can use this partial information about transformer for health index determination. Grey system theory deals with the incomplete information in system analysis. The objective of this paper is, to evaluate the health index of transformers by means of Grey Incidence Analysis (GIA) and Grey Relational Analysis (GRA) for absolute and relative scaling respectively. Synthetic degree of GIA is employed for absolute scaling, where the test samples are compared with industry standard.
However, test samples are compared without applying any standard model in GRA by means of approaching degree. The assessment results from grey analysis are further examined by Adaptive Neuro-Fuzzy Inference System (ANFIS) and Network Fitting (NF) tool. The proposed measurement is promising in priority based maintenance activities of power transformer.

General Terms

Power Transformer state assessment, Grey system Theory

Keywords

Key gases, DGA, Health Index of PT, Grey Incidence Analysis, Grey Relational Analysis, Absolute and Relative scaling.

1. INTRODUCTION

Power Transformer (PT) is one of the significant devices observed in every substation, typically a design life of 20-35 years. However, life extension of transformer as long as 60 years is possible with proper maintenance. Deformation in transformer observed due to thermal, electrical, chemical and mechanical stresses [1]. Hence fault diagnosis becomes increasingly important to keep power systems in normal operation [2]. Several monitoring and testing equipment are preferred to identify the health status of transformer [3]. The health or criticality indices are commonly determined through supervision of various components of transformer [4]. These indices are the effective measures for transformers state ranking [5]. Some technical service groups assign score or condition factor to every component of transformer in preparing the rank within test samples [6-8]. The selection of correct assessment method can only give better health or criticality index from the measured factors. Although, frequent data accumulation from all disseminated test equipment is unrealistic, as some test only conceded by shutting down the operation of transformer. As an alternative, Dissolved Gas Analysis (DGA) is a safe technique of interpretation. The characteristic gases observed in the oil include hydrogen, methane, acetylene, ethylene, ethane, carbon monoxide and carbon dioxide. These seven gases are referred as ‘key gases’ and utilized for DGA. All the information related to DGA is contained in gas guides such as ANSI/IEEE C57.104™ (Revision of IEEE std.) and IEC 60599. Total Dissolved Combustible Gases (TDCG) criteria, mentioned in gas guide [9-10] for condition judgment is shown in Table-1.

Several assessment methods as well as techniques are tried on gas data and some associated parameters of the power transformer. Soft computing techniques such as ANN [11], Neuro-Fuzzy Inference System [12], Fuzzy logic [5, 13] and Genetic algorithm [14] are effectively used in deducing the diagnostics and ranking of transformers. These soft computing methods need ample data of system’s input/output. Results drawn from these computing have shown certain degree of success although the assessment methods were found indistinctive. Applying the statistical or model-free methods can hardly achieve useful solutions. In addition, frequent collection of all the parametric data from power transformer is unrealistic. Hence the assessment method which deals in partial information is requisite for analysis.

Grey theory proposed by J. L. Deng in 1982, deals in partial information i.e. distribution free samples of small size [15] for system analysis. A complete description of grey systems theory on the axioms of uncertainty and grey cognitive principles [16] are strongly treated in mathematical formats. Several methods such as grey incidence analysis, grey sequence generations, and grey GM(1,1) model are commonly used for evaluation, prediction, decision-making, control and optimization[17]. A verity of Grey methods is also introduced in the field of power transformer analysis [18-23]. This paper concerned with the two different assessment methods of grey theory i.e. GIA and GRA, employed on key gas data set for transformer health index calculation and scaling.

Table 1: IEEE specified Gas levels and conditions of transformer

Status	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	TDCG
Condition-1	< 100	< 120	< 35	< 50	< 65	< 350	< 2500	< 720
Condition-2	101-700	121-400	36-50	51-100	66-100	351-570	2500-4000	721-1920
Condition-3	701-1800	401-1000	51-80	101-200	101-150	571-1400	4001-10000	1921-4630
Condition-4	> 1800	> 1000	> 80	> 200	> 150	> 1400	> 10000	> 4630

2. GREY INCIDENCE AND RELATIONAL ANALYSIS

Assuming the behavioral sequence of a factor x_i,

x_i (k) = (x_i(1) , x_i(2) , ... x_i(n)) and

Di a sequence operator satisfying

$X_iD_i = (x_i(1)d_1, x_i(2)d_1, \dots, x_i(n)d_1)$

Definition1: Assume that X is the set of all factors involved in a study of a system, and D the set of all grey incidence operators. Whereas, (X, D) is called the space of grey incidence. Some useful sequence operators and corresponding transform are given as follows.

Table 2: Data normalization operators

Sr. No.	Sequence operators	Transform
1.	Initialing	$x_i(k)d_1 = \frac{x_i\,(\mathrm{k})}{x_i\,(1)}$
2.	Averaging	$x_i(k)d_2 = \frac{x_i(k)}{\overline{X_i}},$
3.	Interval	$x_i(k)d_3 = \frac{x_i(k) - \min_k \{x_i(k)\}}{\max_k \{x_i(k)\} - \min_k \{x_i(k)\}}$
4.	Reversing	$x_i(k)d_4 = 1 - x_i(k)$
5.	Reciprocating	$x_i(k)d_5 = 1/x_i\,(k)$
6.	zero starting point	$x_i(k)d = x_i(k) - x_i(1)$

Proposition: Assume that the images of the zero starting point of two behavioral sequences

$x_i^0 = (x_i^0(1), x_i^0(2), \dots\dots\dots, x_i^0(n))$ and $x_j^0 = (x_j^0(1), x_j^0(2), \dots\dots\dots, x_j^0(n))$

Let, $S_i - S_j = \int_1^n (x_i^0 - x_j^0)\, dt$

Then following hold true.

(a) If x_i^0 is always above x_j^0,then $S_i - S_j \geq 0$;

(b) If x_i^0 is always underneath x_j^0 is always then $S_i - S_j \leq 0$; and

(c) If x_i^0 *and* x_j^0 alternate their positions, the sign of $S_i - S_j$ is not fixed.

Definition 2*:** Assuming two sequences X_i and X_j of the same length, S_i and S_j is defined as in preposition, then $\varepsilon ij = \frac{1+|Si|+|Sj|}{1+|Si|+|Sj|+|Si-Sj|}$ is called the ***absolute degree of grey incidence of X_i and X_j.

Definition 3: $\mathcal{X}i$ *and* $\mathcal{X}j$ are two sequences as that of def.1 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 $0 < \boldsymbol{r_{ij}} < 1$.

Definition 4*:** When general relationship of closeness between sequences is considered, then incidence degree is expressed using, $\boldsymbol{\rho_{ij} = \theta\, \varepsilon ij + (1\text{-}\theta)\ r_{ij}}$ and denoted as ***synthetic degree of grey incidences. Typically θ is set to 0.5, but to realize the relationship between some absolute quantities, greater values can also be useful. If the priority is to observe the rate of change, smaller values of θ is often employed [24]. Absolute, relative and synthetic matrixes of grey incidences are achieved using system characteristic and relevant factors

as follows-

IEEE specified key gases caution levels (Y1 to Y3) are used here as system characteristic and key gas samples of five transformers (X1 to X5) are tested through three different degrees of grey incidences.

Table 3: key gas Caution levels and test samples

Key Gases	System Chart. (IEEE std.)			Sequences of Relevant factors				
	Y1	**Y2**	**Y3**	**X1**	**X2**	**X3**	**X4**	**X5**
H_2	100	700	1800	53	12	1	12	1
CH_4	120	400	1000	49	325	19	8778	73
CO	350	570	1400	748	12	140	317	124
CO_2	2500	4000	10000	6021	787	1879	2959	66260
C_2H_4	50	100	200	2824	1	1	11900	1
C_2H_6	65	100	150	514	3	57	4834	88
C_2H_2	35	50	80	31	108	1	18	1

The Absolute matrix of Incidences estimation is as follows-

$$A = [\varepsilon ij]_{3\times 5} = \begin{pmatrix} 0.6304 & 0.7186 & 0.9096 & 0.5444 & 0.5191 \\ 0.5687 & 0.9148 & 0.8216 & 0.5234 & 0.5101 \\ 0.6476 & 0.6930 & 0.8617 & 0.5503 & 0.5217 \end{pmatrix}$$

The images of Zero stating points of system characteristics and relevant factors are calculated to get the coefficients of Relative matrix of incidences-

$$B = [r_{ij}] = \begin{pmatrix} 0.5696 & 0.6391 & 0.5062 & 0.5054 & 0.5001 \\ 0.5064 & 0.5129 & 0.5005 & 0.5005 & 0.5000 \\ 0.5056 & 0.5112 & 0.5005 & 0.5004 & 0.5000 \end{pmatrix}$$

The Synthetic matrix of incidences with resolving factor i.e. $\theta = 0.5$ is,

$$C = [\boldsymbol{\theta}\ \mathbf{A} + (\mathbf{1}\text{-}\boldsymbol{\theta})\ \mathbf{B}] = [\ \boldsymbol{\theta}\ \boldsymbol{\varepsilon ij} + (\mathbf{1}\text{-}\boldsymbol{\theta})\ \boldsymbol{r_{ij}}\ ]$$

$$C = [\rho_{ij}] = \begin{pmatrix} 0.6000 & 0.6788 & 0.7129 & 0.5249 & 0.5096 \\ 0.537 & 0.7138 & 0.6610 & 0.5119 & 0.5050 \\ 0.5766 & 0.6020 & 0.6811 & 0.5253 & 0.5108 \end{pmatrix}$$

The results from synthetic matrix indicate that Y_1 is the quasi- preferred system (Sum of Row_1=3.0262) characteristic and ranking of relevant factors (key gas test samples of transformers) - $\mathbf{X_3 \geq X_2 \geq X_1 \geq X_4 \geq X_5}$

Where, test sample X_3 (sum of $column_3$ = 2.055) is healthy compare to sample X_5 (1.5254), indicates immediate attention for transformer no.5.

Synthetic degree (SD) of grey incidence is a numerical index that describes the overall relationship of closeness in the interval of 0.5 to 1. Hence, possible health judgment criterion for absolute scaling of transformers using synthetic degree of incidence is -

Table 4: Absolute Scaling Criterion

Absolute Scaling	State of Transformer
DGI >= 0.90	Healthy
DGI >= 0.80	Abs. Normal
DGI >= 0.70	Normal
DGI >= 0.60	Slight fault
DGI >= 0.50	Serious fault

3. GREY RELATIONAL ANALYSIS

To apply GRA, input attributes need to satisfy three conditions given as-

(i) The attributes not less than a magnitude of two.

(ii) All attributes must be of the same type i.e. benefit, cost, or optimization of a specific value.

(iii) All attributes have the same measurement scale, if uses quantitative scale (same unit or no unit).

All the above conditions are referred as *scaling* (for the order of magnitude), *polarization* (for the attribute type), and *non-dimension* (for the measurement scale). The GRA algorithm is specified as follows:

Constructing standard pattern (bull's eye)

Assume W_i is the state model-*i*, and $W(k)$ is the state parameter of sequence-k for constructing the model

- ***Standard state model-*** $\boldsymbol{W_0}$***:***

Assume W_i is the multi-polarity criteria sequence:

W_i = { $W_i(1)$, W_i (2),…………, W_i (n)}

$\forall W_i$ (k) Є W_i=> k Є K={1,2,...,n}, i Є I={1,2,.., m}

Define ω(k) as specification model sequence:

$Wi(K)$ = ($W1(k)$, $W2(k)$, ……. $Wm(K)$)

$\forall$ $W(k)$ Є => $W(k)$ => 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 $Wi(K)$ = POL(max), then W_0 (k) = max $Wi(K)$,

ii)While POL $Wi(K)$ = POL(min), then W_0 (k) = min $Wi(K)$,

iii)While POL$Wi(K)$= POL(mem), then W_0 (k) = avg $Wi(K)$,

Where, $Wi(K)$ Є $W(K)$ for all criteria and the standard pattern sequence will be-

W_0 = {W_0 (1), W_0 (2), ... , W_0 (n)} also called as target heart.

- ***Transforming grey target***

Assume that T is a grey target transform, then

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

Where, X_0 refers to the standard bull‟s eye and X_0(k) Є X_0 => X_0 = T_{w0} ; and, T_{w0} = X_0 = (1, 1…. 1)

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

The coefficient of target heart degree calculate through

$$\gamma\big(x_0(k), x_i(k)\big) = \frac{\{\min_i \max_k \Delta oi(k) + \rho \max_i \max_k \Delta oi(k)\}}{\Delta oi(k) + \rho \max_i \max_k \Delta oi(k)} \quad \ldots.(2)$$

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**.**

ΔO_i (k) = | $x_0(k) - x_i(k)$ | = | 1- $x_i(k)$ | ;

ΔO_i (min) = $min_i\, min_k$min.Δo_{ik} ; ΔO_i(max) = $max_i\, max_k$min.Δo_{ik} ;

Taking the average of the grey relation coefficient to Target heart degree (Jianpo Li et.al.2009) by applying –

$$\gamma\,(X_0\,,\,X_i)) = \frac{1}{n}\sum_{k=1}^{n}\gamma\big(x_0(k), x_i(k)\big) \quad \ldots\ldots (3)$$

The approaching degree (AD) by means of GRA 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

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

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, these seven intervals established an important relationship for state assessment. The relative scaling of transformers refer to approaching degree is possible using the following criterion shown in Table-5.

Table 5: Relative scaling criterion

Approaching Degree i.e. γ	State of Transformer
γ Є[0.90,1]	Healthy
γ Є[0.80,0.90)	Abs. Normal
γ Є[0.70,0.80)	Normal
γ Є[0.60,0.70)	Slight fault
γ Є[0.50,0.60)	Middle fault
γ Є[0.40,0.50)	Serious fault
γ Є[0.33,0.40)	Critical

4. ABSOLUTE AND RELATIVE SCALING OF TRANSFORMERS

Industrial standards are compared with the test samples in absolute scaling. Hence synthetic degree of incidence is used to compare the test samples with three caution levels of gases specified in IEEE/IEC guide. However, relative scaling involves comparison of data without any standard model.

4.1 Grey Methodologies

Both the scaling techniques are further checked using GIA and GRA, employed on key gas set of 281 samples. The classification using synthetic degree of grey incidence on three caution levels as well as absolute scaling using caution level-1 are displayed in Table 6.

Table 6: Absolute Scaling using SD (GIA)

Absolute Scaling	GIA Method
Healthy	03
Abs. Normal	20
Normal	63
Slight fault	86
Serious fault	109
Total No. of Transformers= 281	

Table 7: Relative scaling using AD (GRA)

Degree of Incidences	Caution Level-1	Caution Level-2	Caution Level-3
Absolute	137	62	82
Relative	30	46	205
Synthetic	94	86	101

The test samples are normalized first and then find the approaching degrees (AD) of every sample by GRA procedure. The classification of transformer samples is displayed in Table-7 as above. The results of grey methods for absolute and relative scaling are further examined using ANFIS and NF tool.

4.2. Absolute Scaling using ANFIS and NF

Subtractive clustering option of ANFIS is selected for natural groupings of data which produces a concise representation of a system’s behavior from input-output. A Sugeno-type fuzzy inference system is generated by selecting *genfis2*, builds upon the *subclust* function. Normalized input of seven key gases and the corresponding GIA outputs from synthetic degree (caution level-1) are considered for investigation. The subtractive clustering structure and generated FIS is shown in fig.1 and 2 respectively.

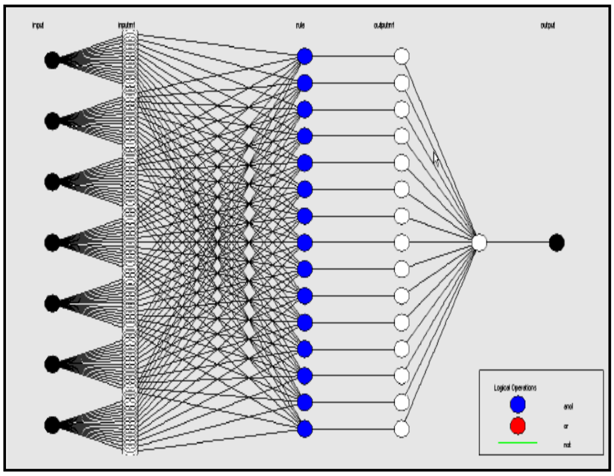

Fig.1: Structure for GIA output

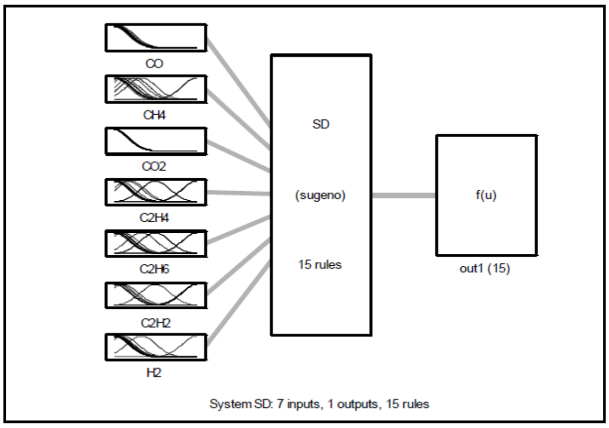

Fig.2: FIS for Synthetic degree (caution level-1)

A neural network maps between a data set of input variables and a set of GIA output. A two-layer feed-forward network with three hidden neurons fit this multi-dimensional mapping problem. The network is trained with Levenberg-Marquardt back-propagation algorithm. The numerical outputs from ANFIS and NF for absolute scaling are represented using stem plot as shown in fig.3 and 4 respectively.

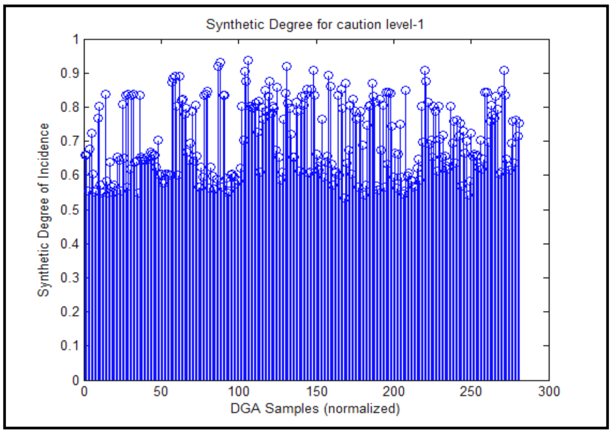

Fig. 3: ANFIS output

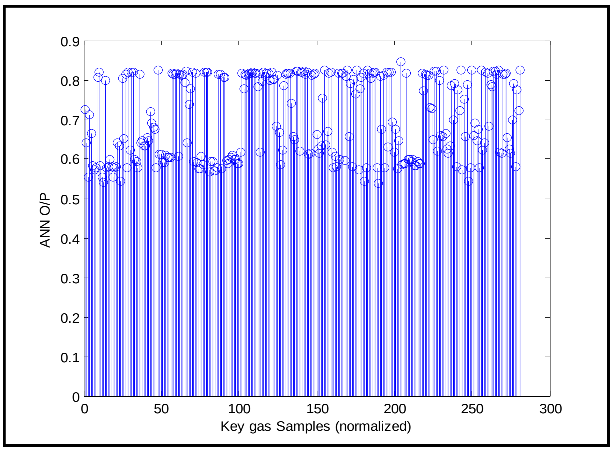

Fig. 4: ANN output

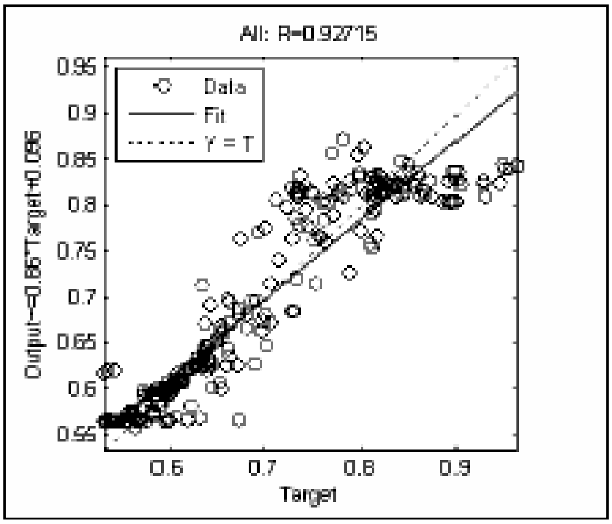

Fig.5: Best fit for SD (caution level-1)

The correlation of 0.9271 is observed for caution level-1. However, the best ANN outcome for synthetic degree on first caution level observed in net_218 at minimum error of 4.825×10^{-4}. The regression result of the network for synthetic degree is shown in fig.5 and classification in fig.6.

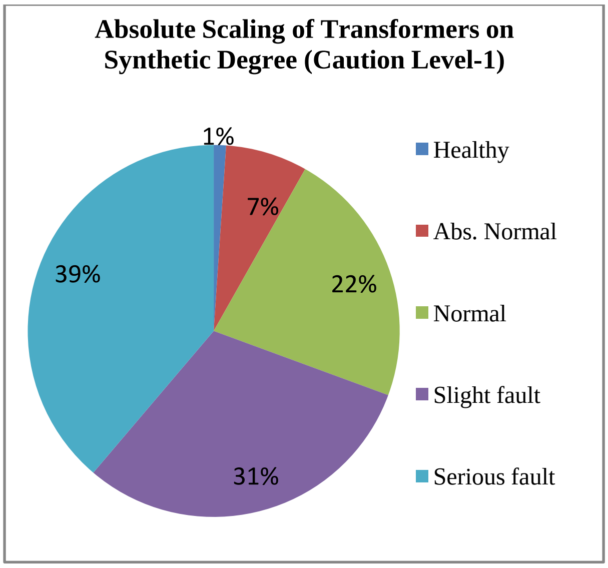

Fig.6: Health categorization

4.3 Evaluation Using Relative Scaling

Adopting the same approach for the relative scaling, the ANFIS and NN are used for GRA. The input-output data set of GRA attempted for subtractive clustering and neural network fitting. The structure and FIS generated is displayed in fig.7 & 8 respectively.

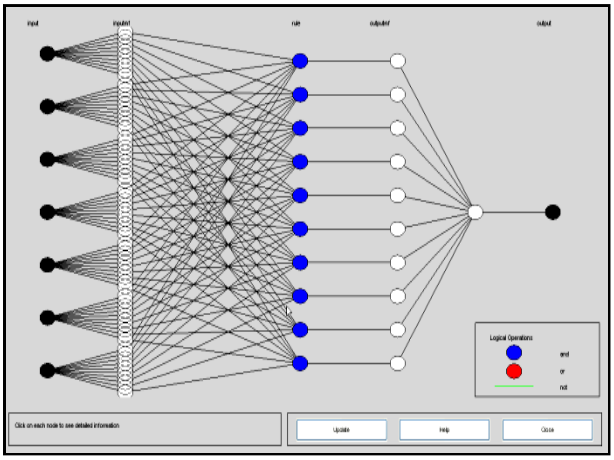

Fig.7: Structure for GRA output

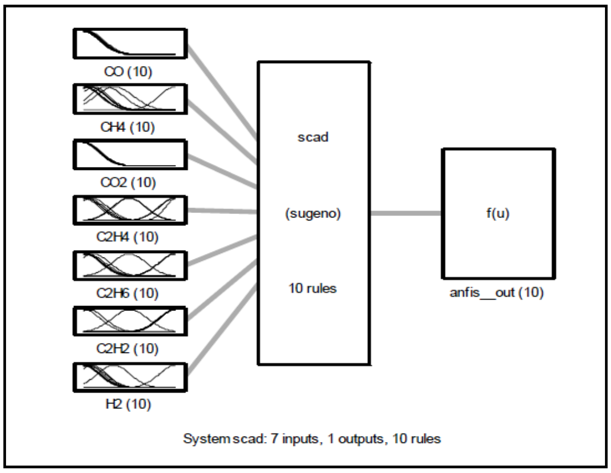

fig.8: FIS for Synthetic degree

The numerical outputs of ANFIS and NF for relative scaling are represented in the following figures (fig.9 &10).

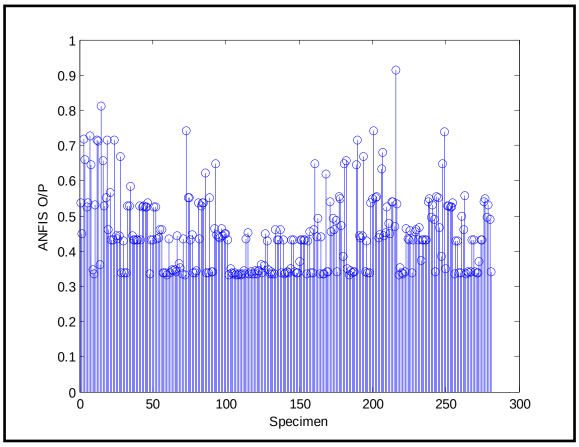

Fig. 9: ANFIS output

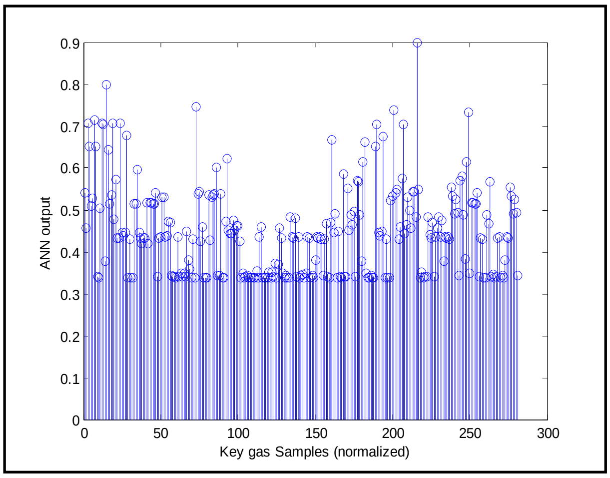

Fig. 10: ANN output

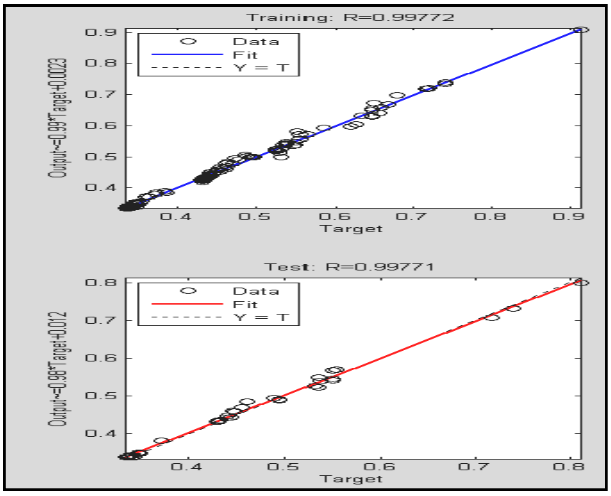

Fig. 11: Best fit for GRA data

The results of the network have found in net_162 shown perfect overall liner relationships of 0.99727 for the given data, same is displayed in fig.11 as above. The fig.12 shows health-wise classification by adopting the relative scaling.

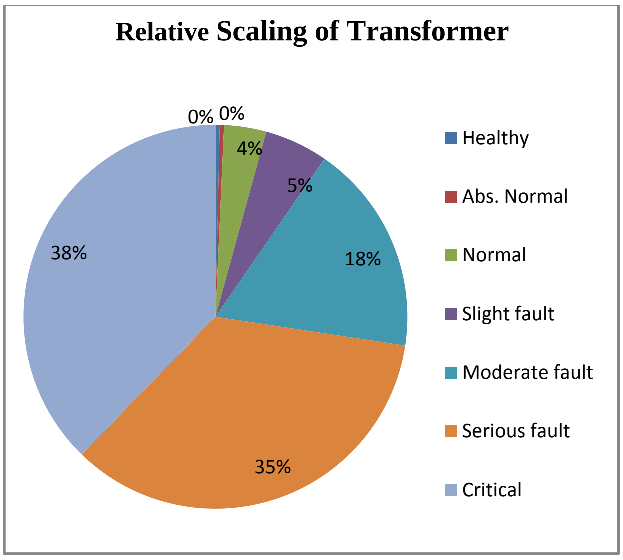

Fig.12: Health categorization

5. CONCLUSIONS

The phenomenon of dissolved-gas-in-oil represents the partial information of a gigantic system like power transformer. The analogy of partial information from grey system theory is utilized here to compute the health index of transformers. Two methods from grey system theory i.e. GIA and GRA are introduced for state assessment. These methods have been demonstrated using key gas samples to calculate their health index. Selecting the resolving coefficient of 0.5 for GIA as well as GRA gives straight forward categorization about transformer health with five and seven grades respectively. These intervals with qualitative notation about the health are further used for absolute and relative scaling of transformers. The benchmarking of GIA and GRA methods are further testified by applying the subtractive clustering option from ANFIS and with network fitting tool of ANN. The outcome of these soft computing techniques has shown better co-relationship for relative scaling compare to absolute scaling. The absolute and relative scaling models presented by means of grey methodologies have shown a certain degree of success in assessing the health condition of working transformers on qualitative and quantitative basis.

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