International Journal of Applied Engineering & Technology

GREY THEORY BASED HYPOTHESIZED MODELS FOR POWER TRANSFORMER SCALING

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ABSTRACT

Several monitoring and testing equipments are utilized in identifying the different faults in a power transformer. An exclusive instrument is preferred to detect a specific fault. However, compilation of different test results input in providing the decisive statement about transformer health. Safe and secure technique, such as Dissolved Gas Analysis (DGA) is useful in identifying the majority of incipient faults, inside the transformer. The dissolved gas-in-oil phenomenon is observed to be analogous to grey system. Grey system theory is an extension of fuzzy set theory, employed for inferior and uncertain information analysis. Grey System Theory (GST) methods are found applicable for DGA data assessment. The objective of this paper is, to assess the health index ranking of transformers by means of Grey Incidence Analysis (GIA) and Grey Relational Analysis (GRA). Absolute scaling performed using synthetic degree of incidences, where in test samples are evaluated on three caution levels. Approaching degree of GRA is utilized for relative scaling, suitable for the judgment of fleet connected transformers. The grey assessment methods are further examined by means of data driven soft computing tools. The proposed measurement is promising in priority based maintenance activities of power transformer.

Key Index – DGA, Health Index of Transformer, Grey System Theory, Grey Incidence Analysis, Grey Relational Analysis, Absolute and Relative scaling.

1. INTRODUCTION

Power Transformer is the significant device in power supply systems. It experiences thermal, electrical, chemical and mechanical stresses during power delivery (D. Kovacevic et al. 2009). The manufacturing company predicts 20-35 years of design life. However, life extension of transformer as long as 60 years is possible with proper maintenance. Hence fault diagnosis and maintenance become increasingly important to keep power systems in normal operation (M. Banovic et al. 2009).Several monitoring and testing equipments are utilized to identify faults in the transformer. However, these dissimilar test results found incompetent in judging the health status of transformer. Alternatively, Dissolved Gas Analysis (DGA) is a safe technique of interpretation (CEATI Report No. T033700-3024, April 2005). An equivalent amount of characteristic gas in the oil indicates the fault exists inside the transformer. Dissolved gases-in-oil include hydrogen, methane, acetylene, ethylene, ethane, carbon monoxide and carbon dioxide. These seven gases are referred as 'key gases' (A. Setayeshmehr et al. 2004).Standards provided for use, analysis, and applications are contained in gas guides such as ANSI/IEEE C57.104™ (Revision of IEEE std.) and IEC 60599 (Edition 2, 1999). According to these standards, Total Dissolved Combustible Gases (TDCG) is one of the useful criteria for condition judgment. TGDC derived from the sum of combustible gas concentrations exceptCO_2.There are four conditions allocated based on TDCG and gas levels. It starts from condition-1 which indicates satisfactory operation of transformer towards condition- 4 for failure.

***Table 1:** IEEE specified Gas level 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

Health or criticality indices are commonly determined through supervision of various components of transformer (A.N.Jahromi et al. 2009). These indices are the effective measures of evaluation for transformers state ranking (A. Abu-Siada et al.2010).Several technical service groups assign score or condition factor to every component of transformer to prepare the rank within test samples (Hydroelectric Research, 2003; Toronto Hydro-Electric System Ltd., 2010; N. Field et al.2002). Soft computing techniques such as ANN with expert system (Wang Z. et. al.1998), Neuro-Fuzzy Inference System (Zhan-Li Sun et al. 2007), Fuzzy logic (A. Abu-Siada et. al.2010; Balint Nemeth et al.2009), and Genetic algorithm (Rui-rui Zheng et al. 2009) effectively deduce the results of different segments of the power transformer.

Results drawn from these computing have shown certain degree of success although the assessment methods were found indistinctive. Applying the statistical methods or model-free methods can hardly achieve useful solutions, where the system information becomes partially available. Adopting the methodologies of GST for dissolved gas-in-oil phenomenon is one of the options for state assessment. GST commonly uses for distribution free samples of small size (Sikun Yang, 2008) for system analysis. Verities of Grey methods are introduced in the field of power transformer analysis(S. Bin et al.2003;J. Yanjun et al.2008;D. Lixin et al.2005; Li Jianbo et al.2008;Fu Mingfu et al.2007; Liu S F et al. 1997). However, the assessment results from grey methods can be tested by means of data driven methods (DDM).It is based on analyzing the data about a system, in particular finding connections between the system state variables (input, internal and output variables) without explicit knowledge of the physical behavior of the system (D. Solomatine, L.M. See and R.J. Abrahart). These methods represent large advances on conventional empirical modeling and include contributions from the following overlapping fields: artificial intelligence (AI), computational intelligence (CI), machine learning (ML), intelligent data analysis (IDA), data mining (DM) and knowledge discovery in databases.

2. Grey Systems Theory

Grey theory proposed by J.L. Deng in 1982.Liu and Lin presented a complete description of grey systems theory. The philosophical development on the axioms of uncertainty and grey cognitive principles (Lin Y. et.al.2006), observed in mathematical format. 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 (Li Q X et al.2010).

2.1 Grey Incidence Analysis

The fundamental idea of GIA is, to find closeness of a relationship on the similarity level with the geometric patterns of sequence curves. This analysis can be employed with a few data points (generally not fewer than (3) and does not require the data to satisfy any pre-determined distribution. Such analysis is used to determine the dominant and secondary observed behavioral data. Currently, many computational formulas of different forms for the calculation of degrees of grey incidence are exist (Liu S. F., and Lin Y. 2006). Some of the definitions are explored below.

2.2 Sequence operators for data Normalization

Assume that x_i is a systems' factors with the k^{th}observation value being x_i *(k), k* = 1,2, ... , n. and If *k* stands for time, then x_i (k) represents an observation of the factorx_i, at the time moment *k* and is called a behavioural time sequence of the x_i.

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

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

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 factors of the system.

Table No.2: *Sequence operators and Transform for data normalization*

Sr.No.	Sequence operators	Transform	*Proposition*
1.	Initialing	$x_i(k)d_1 = \frac{x_i(k)}{x_i(1)}$	These operators never mixed in a single application but utilized based on the practical situation involved.
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	$x_i(k)d_4 = 1 - x_i(k)$	Anegative correlation between a system factor X_i and a system behaviorX_0
5.	Reciprocating	$x_i(k)d_5 = 1/x_i(k)$	X_i with a positive correlation with X_0
6.	zero starting point	$x_i(k)d = x_i(k) - x_i(1)$	NA

2.3 Degrees of Grey Incidences

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.

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

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

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

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 that two sequencesX_i and X_j are of the same length, S_i and S_j are 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. It satisfy the properties of normality, pair symmetry, and closeness but not wholeness. εij is only related to the geometrical shapes and has no effect on moving horizontally. Whereas , $0 < \varepsilon ij < 1$.

Definition 3: 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 $r_{ij}$and $0 < r_{ij} < 1$.The concept of relative degree of grey incidences is quantitative representation of the rate of change of$\mathcal{X}i and \mathcal{X}j$ relative to their starting point.

Definition 4*:** When general relationship of closeness between sequences is considered, then incidence degree is expressed using, $\rho_{ij} = \theta\varepsilon ij + (1-\theta) r_{ij}$ and denoted as ***synthetic degree of grey incidences. Where, εij and r_{ij} are the absolute degree and relative degree of grey incidence of Xi and Xj, and $\theta \in [0,1]$. 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. Relevant degrees of grey incidence can be defined by using the distance function in the n-dimensional space. These matrices of grey incidences are utilized for preferred classifications (Liu S. F., and Lin, Y. 2006).

2.4 Grey Relational Analysis

GRA is one of the evaluation methods of grey system theory, based on the concept of grey relational space. To apply GRA, input attributes need to satisfy three conditions given as-

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

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

(iii) All attributes have the same measurement scale and if in a quantitative scale then needs 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). If these three conditions are not satisfied, then data pre-processing is necessitate prior to GRA processing. The GRA algorithm (shown in fig.1) is then applied on normalized sequence as follows.

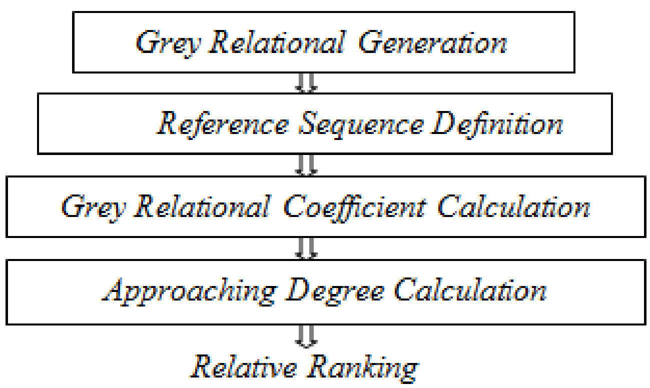

Fig. 1: GRA Procedure

The GRA algorithm is specified as follows:

Step1: The data normalization: $T = \min(x_0, x_i) / \max(x_0, x_i)$

Step2: Deviation sequences: $\Delta 0i = ||x_{0j} - x_{ij}||$

Where, x_{0j} & x_{ij} are reference and comparative sequence

Step3: Grey relational coefficient: $\xi_i(k) = \frac{\Delta \min + \zeta \Delta \max}{\Delta 0i + \zeta \Delta \max}$

Where, Δ min=0 & Δ max=1 and ζ =0.5;

Step4: Approaching Degree: $\gamma_i=\frac{1}{n}\sum_{k=1}^{n}\xi_i(k)$

The reference sequence represents the optimal performance that can be achieved by any of the comparability sequences. Grey relational grade represents the level of correlation between the reference sequence and the comparability sequences.

3. Absolute and Relative Scaling Methodology

In condition based ranking, utilities commonly use absolute and relative scaling. Established industrial standards are compared with the test samples in absolute scaling. However, relative ranking involves comparison of data within the fleet connected of transformers**.** Methodology of both the scaling technique is shown in figure 2 as below.

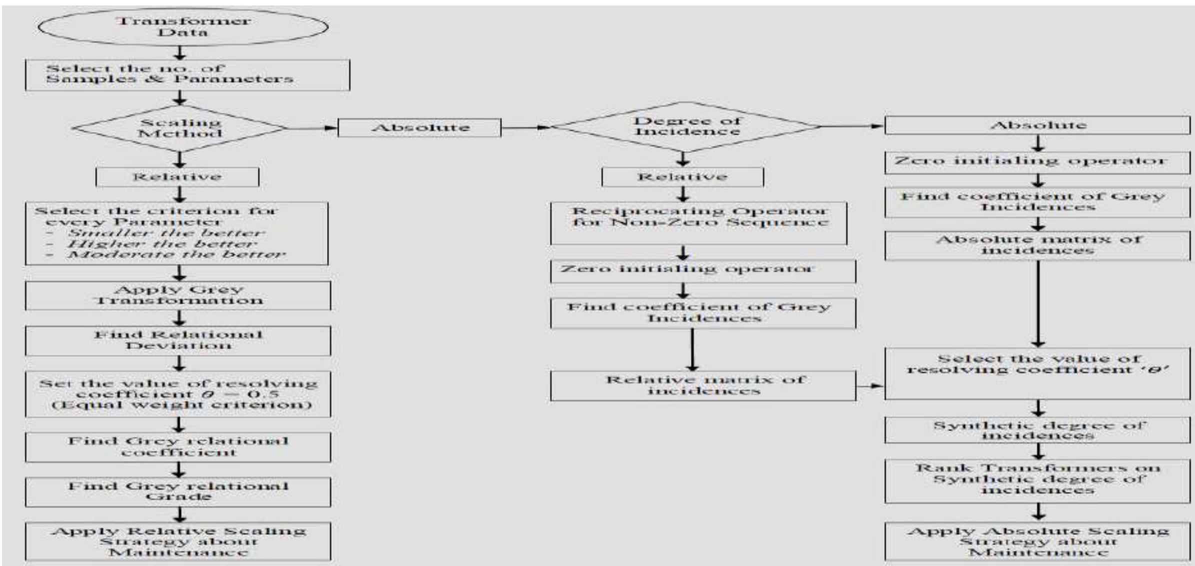

Fig. 2: Algorithm for Absolute and Relative scaling

3.1 Absolute scaling using Synthetic Degree of Grey Incidence

Synthetic degree of grey incidence is used to check the health status of power transformers on three caution levels, specified in IEEE/IEC gas guide. It is observed that results from all the degrees of incidences lies between 0.5 and 1. Therefore, for absolute scaling of transformers, health judgment criterion for synthetic degree of incidences is preferred as follows.

Table 3: Absolute scaling Strategy

Synthetic Degree	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

Key gas samples of 281 transformers are examined on absolute degree of grey incidence. Initially, zero staring point sequence operator is applied for transformation. Then system characteristic (Caution levels) and behavioral sequences (key gas concentration) with relevant factors are compute using the coefficients of absolute degree. In relative degree of incidences, the initial images of system characteristic and relevant factors are obtained through non-zero initial value. Thereafter, compute the system characteristics and the relevant factors by applying zero staring point sequence operator. Relative order of incidences finds through angle of rate of change at each moment of the observation data w.r.t. their initial points. The coefficients are used to form absolute and relative matrix of incidences of size 3 $\times$ 281. Synthetic degree of grey incidence finds the overall relationship of closeness between the two sequences by making the use of absolute and relative degree of incidences. The coefficients of synthetic degrees of size 3 $\times$ 281 are found by selecting the resolving factor at 0.5. The classification result of clustering is summarizes in Table-4 as follows-

Table 4: Grey Clustering outcome

Degree of Incidences	Caution Level-1	Caution Level-2	Caution Level-3
Absolute	137	62	81
Relative	30	46	206
Synthetic ($\theta = 0.5$)	94	86	101
***Total no.** of samples =281*			

The results have shown absolute scaling of transformer with three different degrees of incidences for three caution levels. However, synthetic degree of grey incidence is a numerical index that describes the overall relationship of closeness and hence chosen for absolute scaling model. The Synthetic degree of grey incidence are further measured on three caution levels for 281 test samples and the classification is shown in Table-5 as below.

Table 5: Absolute scaling on Synthetic Degree of Grey Incidence

Absolute Scaling	Assessment Method		
State of Transformers	Synthetic Degree of Grey Incidence		
	Sy-1	Sy-2	Sy-3
Healthy	16	10	10
Abs. Normal	55	54	39
Normal	59	55	92
Slight fault	90	86	85
Serious fault	61	76	55

3.2 Relative scaling by means of GRA

The Grey Relational Grade (GRG)or Approaching Degree is accomplished using-

$$\Gamma(X_0,X_i) = \frac{1}{n}\sum_{k=1}^{n} \gamma\ [X_0(k), X_i(k)]$$

It ranks all the alternatives into: [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] intervals. The concentration of every gas is equally important in making a decision on health of transformer. Therefore, equal weights are considered for every attributes i.e. taking the resolving coefficient at ρ = 0.5, then

$$\Gamma(X_0, X_i) \geq \frac{\rho}{1+\rho} = 0.33333$$

Based on above basic principle, the Approaching Degree separated each alternative 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]. However, the outcome of approaching degree in terms of these seven intervals established an important relationship for state assessment. The grade of transformers in terms of approaching degree is further split into seven categories as shown in Table-6.Grey relational analysis is applied on 281 key gas samples. The samples are normalized and then find the approaching degrees of every sample by employing the GRA produces. The classification of transformer samples is displayed in Table-7as follows-

Table 6: Relative scaling strategy

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

Table 7: Relative scaling on Approaching Degree

Relative Scaling	Assessment Method
State of Transformers	**Approaching Degree from GRA**
Healthy	01
Abs. Normal	01
Normal	10
Slight fault	15
Middle fault	50
Serious fault	98
Critical	106

4. Data driven Models for Confirmation of Grey Assessment methods

The hypothesized assessment methods from grey theory, utilized for absolute and relative scaling, are initiated to parameterize the model structures in ANFIS and ANN computing. ANFIS is a hybrid intelligent system, implements a Sugeno fuzzy inference system for a systematic approach to generate fuzzy rules from a given input/output dataset. If the information about number of clusters for a given set of data is uncertain, then subtractive clustering method offers better option, intended for high dimension problems. The neural network fitting tool creates and trains a network and evaluates its performance using mean square error and regression analysis. A code developed in 'C' utilized for selection of superior network among the others on least error.

4.1 Evaluation of Absolute Scaling

The grid partitioning method is restricted to six attributes because of the limitations of dimensionality problem. Hence the function of clustering is used to identify natural groupings of data from a large data set which produce a concise representation of a system's behavior. Fuzzy tool helps in finding the clusters in input-output training data. A Sugeno-type fuzzy inference system is the best model which shows the data behavior using a minimum number of rules. The rules partition themselves according to the fuzzy qualities associated with each of the data clusters. Initialing operator is used to normalize the concentration of the gases, given in DGA data sheet. Normalized input samples and the corresponding GIA outputs from synthetic degree are considered for modeling. Subtractive clustering executed on GIA outcome for absolute scaling. The FIS is generated by selecting *genfis2* function builds upon the *subclust* function provides a fast, one-pass method which takes input-output training data. The outcome of synthetic degree of grey incidences for caution level-1 and the normalized samples of seven key gases are used to develop a FIS. The subtractive clustering structure and generated FIS is shown in fig.3 and 4.

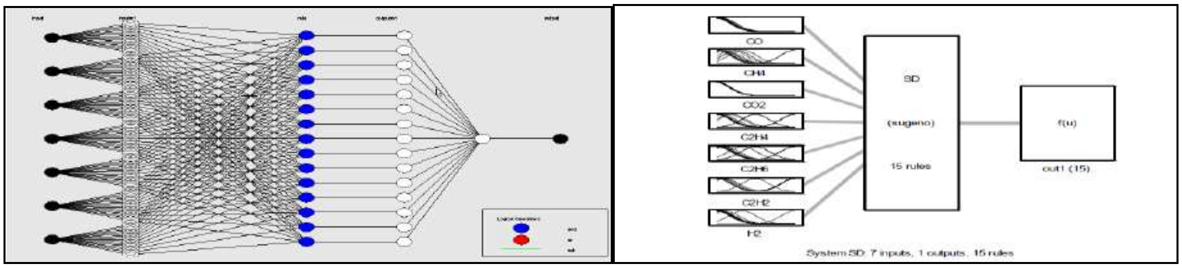

Fig.3: Clustering Structure and FIS for Synthetic degree (for caution level-1)

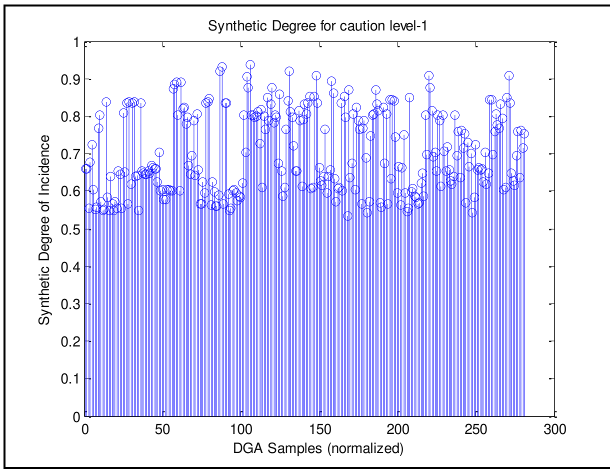

Fig. 4: ANFIS output

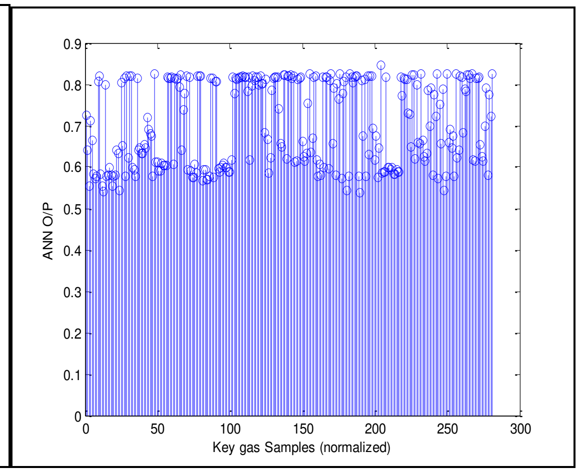

Fig. 5: ANN output

A neural network maps between a da ta set of input variables and a set of GIA outputs as targets. 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 of ANN network for absolute scaling are represented using stem plot as shown in fig.5. The correlation of 0.9271, 0.9201 and 0.9271 is observed for these three caution levels. However, the best ANN outcome for synthetic degree on first caution level observed in net_218 at minimum error of 4.825. The synthetic degree for second caution level is found in net_62 with minimum error of 4.712. However, for third level, the minimum error of 4.825 is observed at net_260. The regression results of the network for synthetic degree (for three caution levels) are shown in the next figure.

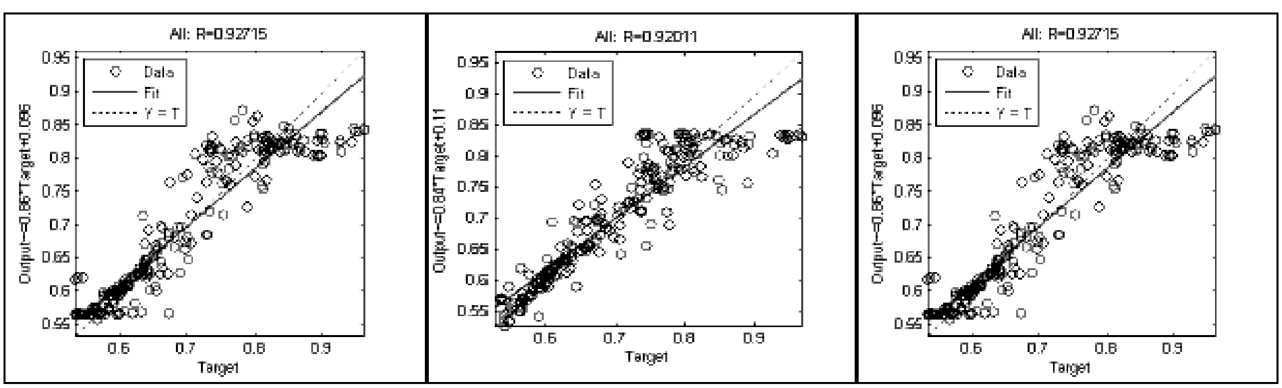

Fig.6: Best fit for Synthetic degree (caution level-1, 2 and 3)

4.2Evaluationof 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 tool.

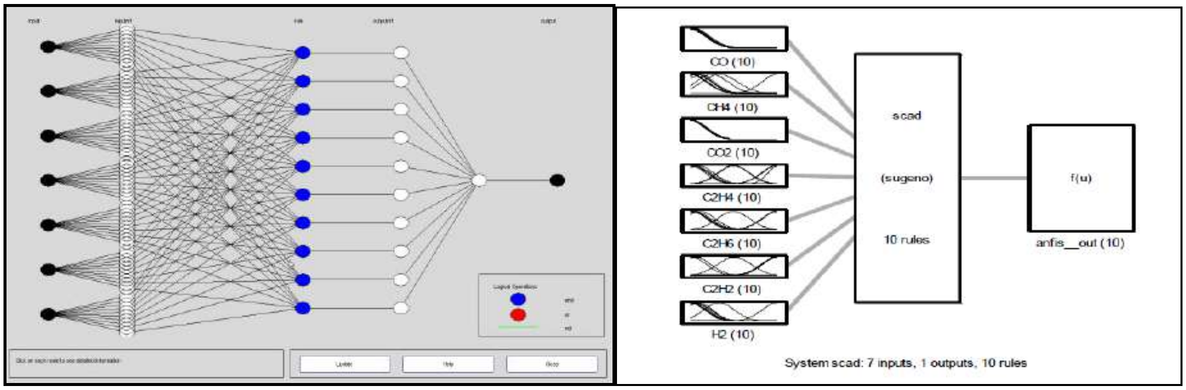

Fig.7: Clustering Structure and FIS to find Approaching degree

The numerical outputs of ANFIS and Neural network for relative scaling are represented using stem plot as shown in the following figures.

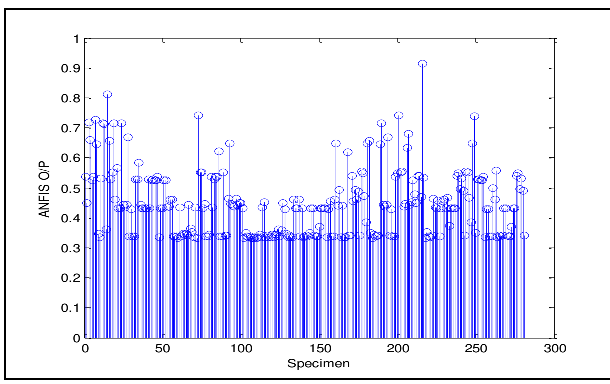

Fig. 8: ANFIS output for 281 samples

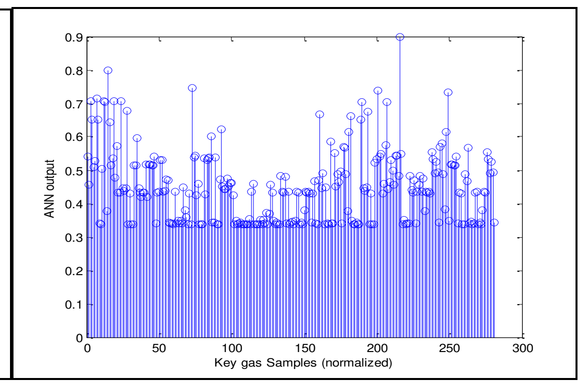

Fig. 9: ANN outcomes for GRA data

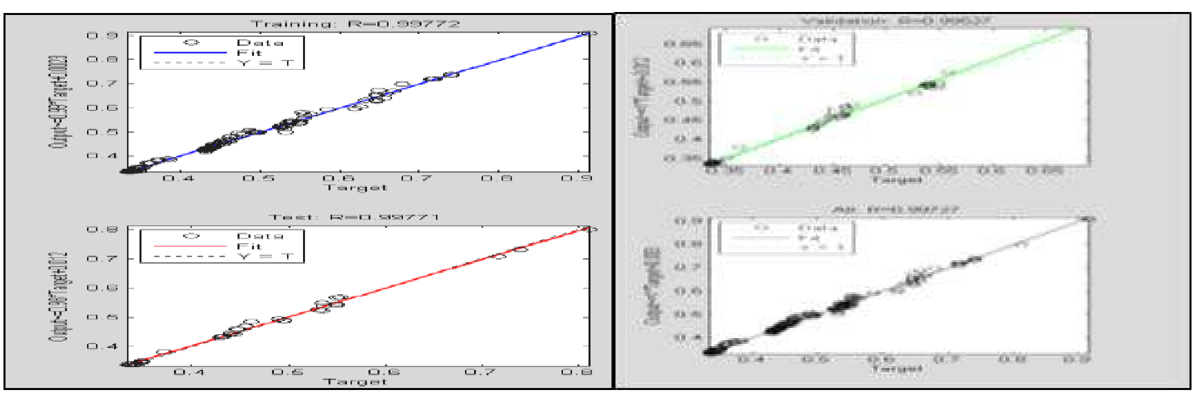

Fig. 10: Best fit for GRA data

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.10 as above.

5. CONCLUSIONS

There are numerous methods and techniques employed to judge the health of power transformer. However, Preliminary source of information related to transformer heal this DGA. The phenomenon of Dissolved gas-in-oil observed analogous to grey system. As grey system deals in partial information, two methods from grey system theory are preferred for assessment purpose. The different Absolute degree, relative degree and synthetic degree of grey incidences have shown diversified outcome for same test samples. As synthetic degree of grey incidences combines the results of Absolute and relative degree of grey incidences hence utilizes for absolute scaling of transformers. The results from synthetic order of incidences with resolving coefficient of 0.5 generate three stage hierarchical results on caution levels of gases. Absolute scaling is logically possible by means of five different health statuses. However, for relative scaling the relational grade with resolving coefficient of 0.5 produced Approaching degree with seven intervals (health statuses). Benchmarking of GIA and GRA methods observed excellent in interpretation and successfully implemented on multiple of DGA samples. The absolute and relative scaling models presented by means of grey methodologies have shown certain degree of success in assessing the health condition of power transformers on qualitative and quantitative basis.

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