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Grey Theory based ANN Approach for State Assessment of Power Transformer

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***Abstract*—Power transformers are key component because power system operation depends on it. The reliability of Power Transformer is essential and hence the monitoring of such important equipment is necessary at substation level. The assessment techniques of power transformer include various methods. Dissolved Gas Analysis (DGA) is a universally accepted and highly recommended technique for fault diagnosis of Power Transformer. There are several DGA methods for detection of faults to measure the concentration in particle per million (ppm) in oil sample. Gas concentrations indicate the fault type and accordingly health of Power Transformer can be judge.**

This paper introduces Grey Theory approach in which analysis is carried out based on partial information to help in standardizing DGA interpretation techniques and to identify transformer state assessment through it. Grey Theory is perfectly matched to the said problem as the DGA samples are less. The keystone of Grey Theory is to find target heart degree and from that making a decision. The key gases are used for Grey analysis. Proposed Grey Model is validated in soft computing tool Artificial Neural Network (ANN). The results of ANN are compared with Proposed Grey Model output. The ANN model shows certain degree of success to validate benchmark of Proposed Grey Model.

***Keywords*—ANN, DGA, Grey Model, Key Gases, State Assessment**

I. INTRODUCTION

Power transformers are a vital link in a power system. Monitoring and diagnostic techniques are indispensable to reduce maintenance and get better consistency of the equipment. Currently there are several of chemical and electrical diagnostic techniques applied for power transformers [1]. The electrical windings in a power transformer consist of paper insulation immersed in insulating oil, hence transformer oil and paper insulation are crucial sources to detect incipient faults, fast developing faults, insulation trending and generally reflects the health condition of the transformer. During faults and due to electrical and thermal stresses, oil and paper decomposition occur evolving gases hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4) and ethane (C_2H_6). DGA is widely used to detect incipient faults [2, 3]. In the fault system of power transformer, it has uncertainty for the relation of conditionality between dissolved gases. It has not specific qualitative and quantitative classification which gases appear because of one certain fault. So the fault system of power transformer can be recognized as a typical grey system. The theory has particular function to deal with model recognition of small sample and poor information. It is one of the effective methods for Multi-objective decision-making [4]. ANN is a new paradigm for computing that gives more performance to throw at problems. It can be used where algorithmic solution cannot formulate, where lots of example of the behavior, where need to pick out the structure from existing data etc.

II. GREY THEORY

Grey system theory or Grey target theory or Grey theory was presented by Prof. Julong Deng in 1980s. This theory is suitable for handling less data, incomplete information and devoid of experience. In this theory, a system is said to be a ‘grey system’ usually, if its information are wholly unknown; while ‘whitening system’ means that the information of a system are complete; If the information of a system are partly known and partly unknown, it means that the system has greyness, which is said to be ‘grey system’. Recently, some researchers have applied grey relational analysis for multi-criteria vague decision making. But only grey relational analysis has been applied in multi criteria vague decision making. But in various practice, there is no given standard scheme for reference. Target Heart Degree determined by grey system theory reflects the integrated sequence of interaction and impact of all factors. In the proposed model, the reference sequence can be constructed from those sequences to be analyzed [4, 5].

III. KEY GAS METHOD

The standard of the Key Gas method is based on the quantity of fault gases released from the insulating oil when a fault occurs which in turn raise the temperature in the power transformer. The existence of the fault gases depends on the temperature or energy that will break the link or relation of the insulating oil chemical structure. This method uses the individual gas rather than the calculation of gas ratios for detecting fault. The significant and proportion of the gases are called key gases [6]. Transformer in-house faults are divided into thermal and electrical categories. Each fault category evolves particular characteristic gases. However, the analysis is not always straight forward as there may be more than one fault present at the same time. From the type and amount of gas, the fault nature can be determined. Various faults produce energy from low level to very high level sustained arcing. The low level energy is a partial discharge which produces H_2 and CH_4. The arcing is capable of generating all gases including C_2H_2. Except for CO and CO_2, all other gases are formed due to the decomposition of oil. CO and CO_2 in DGA represent a good source of paper monitoring. Presence of C_2H_2 in the oil is an indication of high energy arcing [6].

IV. PROPOSED GREY MODEL FOR KEY GAS TECHNIQUE

In this section, Propose Grey Model is developed to estimate transformer Target Heart Degree based on DGA results. The 169 DGA samples of different Power Transformers are collected on which Grey Target Theory is applied. Out of 169, most of the samples are in the category of *faulty* cases. In this section 9 samples of Key gases are discussed to find Target Heart Degree. Input sequences to be analyzed are the 5-key gases in parts per million (ppm) as shown in Table 1. The grey target algorithm [4, 5] to calculate target heart degree of proposed grey model for key gas technique is described as follows:
i=1, 2,3 ,4, 5, 6, 7, 8, 9(nine samples) and k=1,2,3,4,5 (five gases)

***Table 1:* key gases samples**

Sample	CH_4	C_2H_4	C_2H_6	C_2H_2	H_2
1	372	1658	208	10	62
2	328	1462	205	10	55
3	128	1	23	0.01	2349
4	132	1	25	0.01	2460
5	2	3	1	0.01	2
6	116	265	28	204	88
7	169	26	56	0.01	2152
8	164	0.01	54	25	2291
9	153	22	46	0.01	2936

Step 1: Constructing Standard Pattern
Assume ω_i is the state model-i, $\omega(k)$ is the state parameter sequence-k for one certain equipment, constructing the standard state model ω_0
$\omega_i = \{ \omega_i(1), \omega_i(2),.....,\omega_i(n)\}$
$\forall\ \omega_i(k) \in \Rightarrow k \in K=\{1,2,...,n\},\ i \in I=\{1,2,..,m\}$
K refers to the k^{th} criteria.
Define $\omega(k)$ as specification model sequence.
$\omega(k)=(\omega_1(k), \omega_2(k),..., \omega_m(k))$
$\forall\ \omega_i(k) \in \Rightarrow \omega(k) \Rightarrow i \in I=\{1,2,..,m\}$
Usually polarity of specification includes maximum polarity, minimum polarity and moderation polarity as POL(max), POL(min), POL(mem) respectively [4]-[5], therefore
when POL $\omega_i(k)$ = POL(max), then $\omega_0(k) = \max_i \omega_i(k),\ \ \omega_i(k) \in \omega(k)$
when POL $\omega_i(k)$ = POL(min), then $\omega_0(k) = \min_i \omega_i(k),\ \ \omega_i(k) \in \omega(k)$
when POL $\omega_i(k)$ = POL(mem), then $\omega_0(k) = \mathrm{avg}_i\ \omega_i(k),\ \ \omega_i(k) \in \omega(k)$
And then the sequence $\omega_0 = \{ \omega_0(1), \omega_0(2),..., \omega_0(n)\}$ as the standard state model or target heart.
Polarity is selected as per decision requirement [4, 5]. In this case minimum polarity is chosen because lower values of gas concentrations are desired for better health of power transformer. Therefore standard state model is:

$$\omega_0 = \{2, 0.01, 1, 0.01, 2\}$$

Step 2: Transforming Grey Target
To normalize the original data in the range of 0 to 1 grey target transform is used. Assume that T is a grey target transform [4, 5], then

$$T\omega i(k) = \frac{\min\{\omega i(k), \omega 0(k)\}}{\max\{\omega i(k), \omega 0(k)\}} \qquad (1)$$

Therefore grey target transforming coefficients are
$T\omega_0 = x_0 = (1, 1, 1, 1, 1)$
$T\omega_1 = x_1 = (0.00538, 0.00001, 0.00481, 0.001, 0.03226)$
$T\omega_2 = x_2 = (0.0061, 0.00001, 0.00488, 0.001, 0.03636)$
$T\omega_3 = x_3 = (0.01562, 0.01, 0.043478, 1, 0.00085142)$
$T\omega_4 = x_4 = (0.01515, 0.01, 0.04, 1, 0.00081)$
$T\omega_5 = x_5 = (1, 0.00333, 1, 1, 1)$
$T\omega_6 = x_6 = (0.0172, 0.00004, 0.03571, 0.00005, 0.02273)$
$T\omega_7 = x_7 = (0.01183, 0.00038, 0.01786, 1, 0.00093)$
$T\omega_8 = x_8 = (0.0122, 1, 0.01852, 0.0004, 0.00087)$
$T\omega_9 = x_9 = (0.01307, 0.00045, 0.02174, 1, 0.00068)$

Step 3: Calculating Different Information Space
Different information space [4, 5] is the difference between the $x_0(k)$ and $x_i(k)$ i.e. difference between standard pattern and specific pattern grey target transform. It is calculated by using formula:

$$\Delta_{oi}(k) = |\ x_0(k) - x_i(k)\ | = |\ 1 - x_i(k)\ | \qquad (2)$$

$x_0(k) \in x_0 \Rightarrow x_0 = T\omega_{0,}$ i=1, 2, 3, 4 ,5, 6, 7, 8, 9 and k=1,2,3,4,5; where $\Delta_{0i}(k)$ shows the grey relational different information between evaluated sequence $x_0(k)$ and $x_i(k)$.
Δ_{01}= (0.9946, 0.9999, 0.9951, 0.999, 0.96774)
Δ_{02}= (0.9939, 0.9999, 0.9951, 0.999, 0.9636)
Δ_{03}=(0.9843, 0.99, 0.95652, 0, 0.9991)
Δ_{04}= (0.9848, 0.99, 0.96, 0, 0.9991)
Δ_{05}= (0, 0.9966,0,0, 0)
Δ_{06}= (0.9827, 0.9999, 0.9642, 0.9999, 0.9772)
Δ_{07}= (0.9881, 0.9996, 0.9821, 0, 0.999)
Δ_{08}= (0.9878, 0, 0.9814, 0.9996, 0.9991)
Δ_{09}= (0.9869, 0.9995, 0.9782, 0, 0.9993)
From the complete matrix of different information space; *minimum* and *maximum* value are selected. Therefore,
$\Delta_{0i}(\max)=\max_i \max_k \Delta 0i(k) = 0.9999$
$\Delta_{0i}(\min)=\min_i \min_k \Delta 0i(k) = 0$

Step 4: Calculating Coefficient of Target Heart
The coefficient of target heart [4, 5] is calculated by using formula,

$$\gamma\big(x0(k), xi(k)\big) = \frac{\min_i \max_k \Delta oi(k) + \rho \max_i \max_k \Delta oi(k)}{\Delta oi(k) + \rho \max_i \max_k \Delta oi(k)} \qquad (3)$$

Where ρ is the resolving coefficient, $\rho \in [0,1]$. This coefficient is a free parameter. Its value, over a broad appropriate range of values, does not affect the ordering of the grey relational grade values. Assume ρ=0.5. Grey target coefficients obtained for sample '1' are:
$\gamma(x_0(1),x_1(1))=0.3345$, $\gamma(x_0(2),x_1(2))=0.3333$, $\gamma(x_0(3),x_1(3))=0.3344$, $\gamma(x_0(4),x_1(4))=0.3335$, $\gamma(x_0(5),x_1(5))=0.3406$
Similarly for remaining samples coefficients can be obtained.

Step 5: Calculating Target Heart Degree
Target Heart Degree [4, 5] is calculated by using formula,

$$\gamma(x_0,x_i)=\frac{1}{n}\sum_{k=1}^{n} \gamma\big(x0(k), xi(k)\big) \qquad (4)$$

By substituting the coefficients calculated from equation (3) in equation (4); Target Heart Degree obtained for sample '1' is

$$\gamma(x_0,x_1)=\frac{1}{5}\sum_{k=1}^{5} \gamma\big(x0(k), x1(k)\big) = 0.3353$$

Similarly for other samples the target Heart Degree is calculated by applying grey target algorithm. Table 2 shows the input key gases for Proposed Grey Model and their corresponding calculated target heart degree. Target heart degree has value in range of 0 to 1. State of power transformer is decided from the value of target heart degree. More is the value of Target Heart Degree better is the condition of power transformer. Lower is the value of target heart degree means power transformer state goes on deteriorating.

***Table 2*: Target Heart Degree Calculated by Proposed Grey Model for Key Gas Technique**

Sample	CH_4	C_2H_4	C_2H_6	C_2H_2	H_2	Target Heart Degree
1	372	1658	208	10	62	0.3353
2	328	1462	205	10	55	0.3355
3	128	1	23	0.01	2349	0.4698
4	132	1	25	0.01	2460	0.4696
5	2	3	1	0.01	2	0.8668
6	116	265	28	204	88	0.3367
7	169	26	56	0.01	2152	0.4680
8	164	0.01	54	25	2291	0.4681
9	153	22	46	0.01	2936	0.4682

The Grey model output for sample '1' and sample '2' is 0.3353 and 0.3355 respectively on the scale from 0 to 1 which is very low which indicates *faulty* condition of transformer. The excess quantity of ethylene and ethane indicates presence of Thermal Fault. The presence of ethylene may be due to overheating or improper cooling of transformer. The excess quantity of methane indicates Partial Discharge fault also.

The Grey model output for sample '3' and sample '4' is 0.4698 and 0.4696 respectively on the scale from 0 to 1 which is medium low which indicates *middle fault* condition of transformer. The excess quantity of hydrogen indicates presence of Corona Effect due to degradation of solid insulation.

The Grey model output for sample '5' is 0.8668 which is high; it indicates the *normal* condition for transformer. The DGA results indicate concentration of dissolved gases in oil is well within normal limits.

The Grey model output for sample '6' is 0.3367 which is low which indicates *faulty* condition of transformer. The excess quantity of ethylene and acetylene indicates presence of Thermal Fault and arcing respectively.

The Grey model output for sample '7', '8',' '9' is medium low indicate *medium fault* condition. The DGA result shows excess quantity of hydrogen which denotes presence of Corona Effect.

Similarly Grey Target Theory applied on 169 DGA samples of oil and their Target Heart Degree calculated by using Grey algorithm steps. Fig. 1 shows the graph of variation of Target Heart Degree obtained for 169 DGA samples of data. In all 169 DGA samples maximum samples are in the category of *faulty* cases. Target heart degree calculated for these *faulty* samples are low in range of 0.3 to 0.5 which agrees the Power Transformer has fault for such cases.

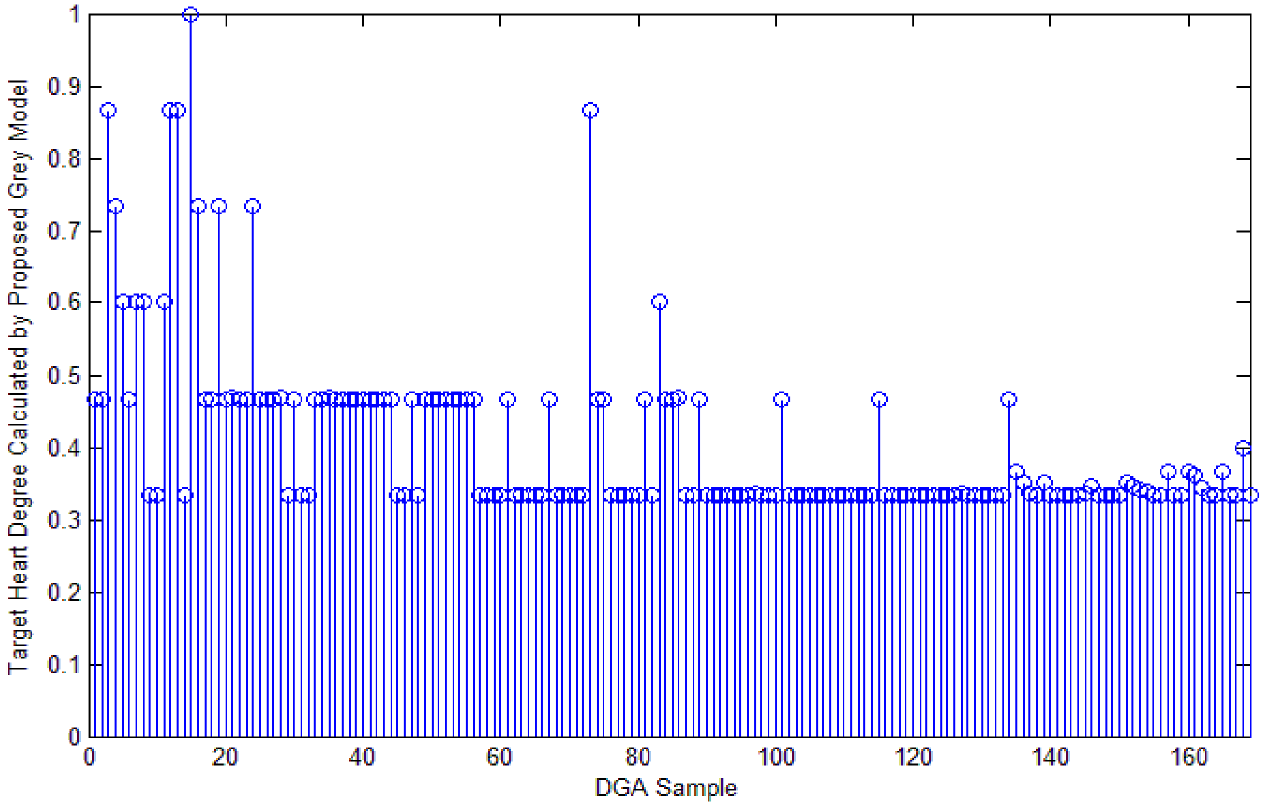

Fig. 1 **Graph of Target Heart Degree**

V. VALIDATION OF PROPOSED GREY MODEL FOR KEY GAS TECHNIQUE IN ANN

The proposed grey model for DGA technique is validated using ANN. ANN is modeled for proposed grey model for key gas technique. ANN is trained for respective input variables of DGA technique from DGA samples along with corresponding output variable of proposed grey model for DGA technique.

In this case of proposed grey model for key gas technique, ANN is trained for five input variables such as CH_4, C_2H_4, C_2H_6, C_2H_2, H_2 and Target Heart Degree output variable of proposed grey model for key gas technique. The output of the ANN model is the Target Heart Degree which is compared with the target heart degree of proposed grey model. A *Neural Network Fitting* Tool is used as an ANN tool available in Matlab for the training of inputs and targets.

The training data is selected as input representing 169 samples of 5 key gases and as target representing 169 outputs (target heart degree) of proposed grey model for training the ANN. After selection of data ANN randomly divide total samples into three sets training, validation and testing. By default 70% data is chosen as training data, 15% data is chosen for testing and 15 % data is chosen for validation. Training data are presented to the network during training, and the network is adjusted according to its error. Validation data are used to measure network generalization, and to halt training when generalization stops improving. Testing data have no effect on training and so provide an independent measure of network performance during and after training. After dividing the data, the number of hidden neurons is set; by default it is 20. The number of neurons can be changed if network does not perform well. Training automatically stops when generalization stops improving, as if there is increase in the mean square error of the validation samples. Training multiple times will generate different results due to different initial conditions and sampling.

VI. ANN MODEL RESULTS

Table 3 shows the comparison of output obtained from Proposed Grey Model and ANN Model for nine DGA samples. The target Heart Degree obtained from ANN model is nearly same as target Heart Degree obtained from proposed grey model. Fig. 2 shows the comparison graph between Proposed Grey Model output and output obtained from ANN for 169 DGA samples of data. Fig. 3 shows percentage error graph between Proposed Grey Model output and output obtained from ANN Model for 169 DGA samples of data. By taking Proposed Grey Model as benchmark the Root Mean Square Error calculated for ANN model is only 14.7 % for 169 DGA samples.

***Table 3*: Output comparison**

Sample	Target Heart Degree Calculated from Proposed Grey Model	Target Heart Degree obtained from ANN Model
1	0.3353	0.33552
2	0.3355	0.33548
3	0.4698	0.46985
4	0.4696	0.46833
5	0.8668	0.86367
6	0.3367	0.33770
7	0.4680	0.46786
8	0.4681	0.46741
9	0.4682	0.46742

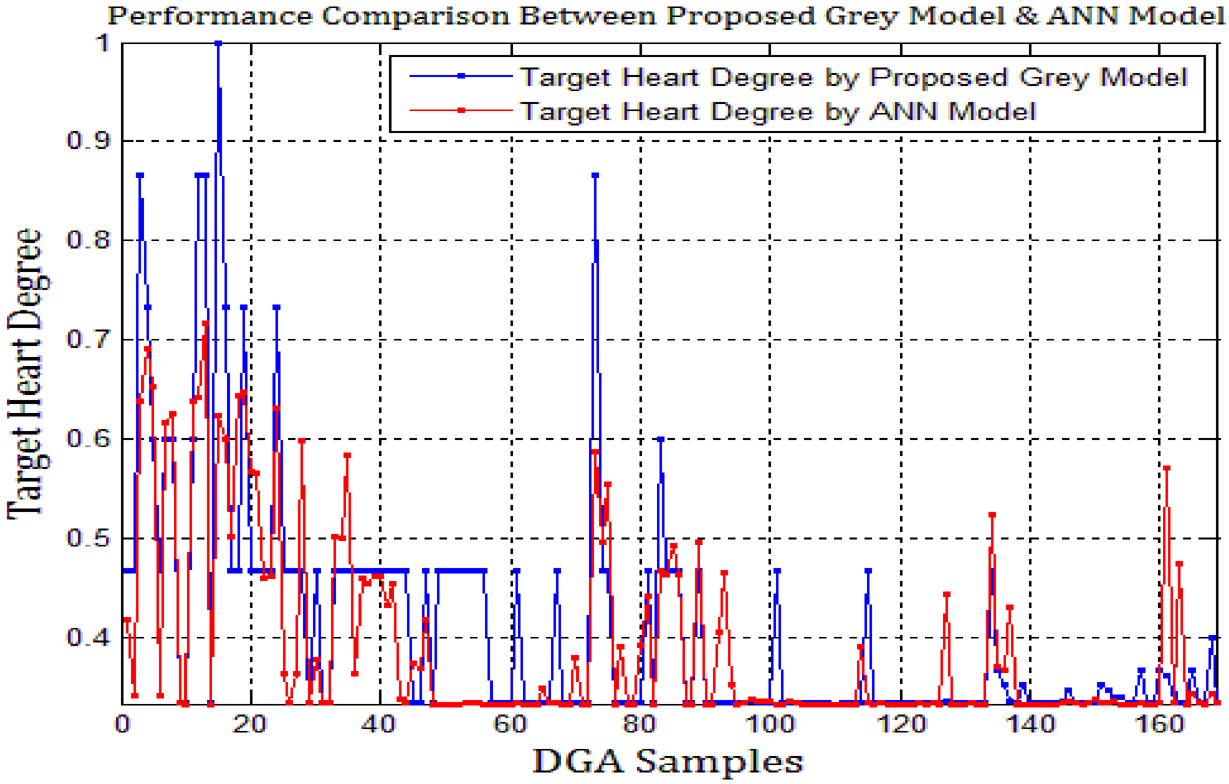

Fig. 2 **Graphical Output Comparison**

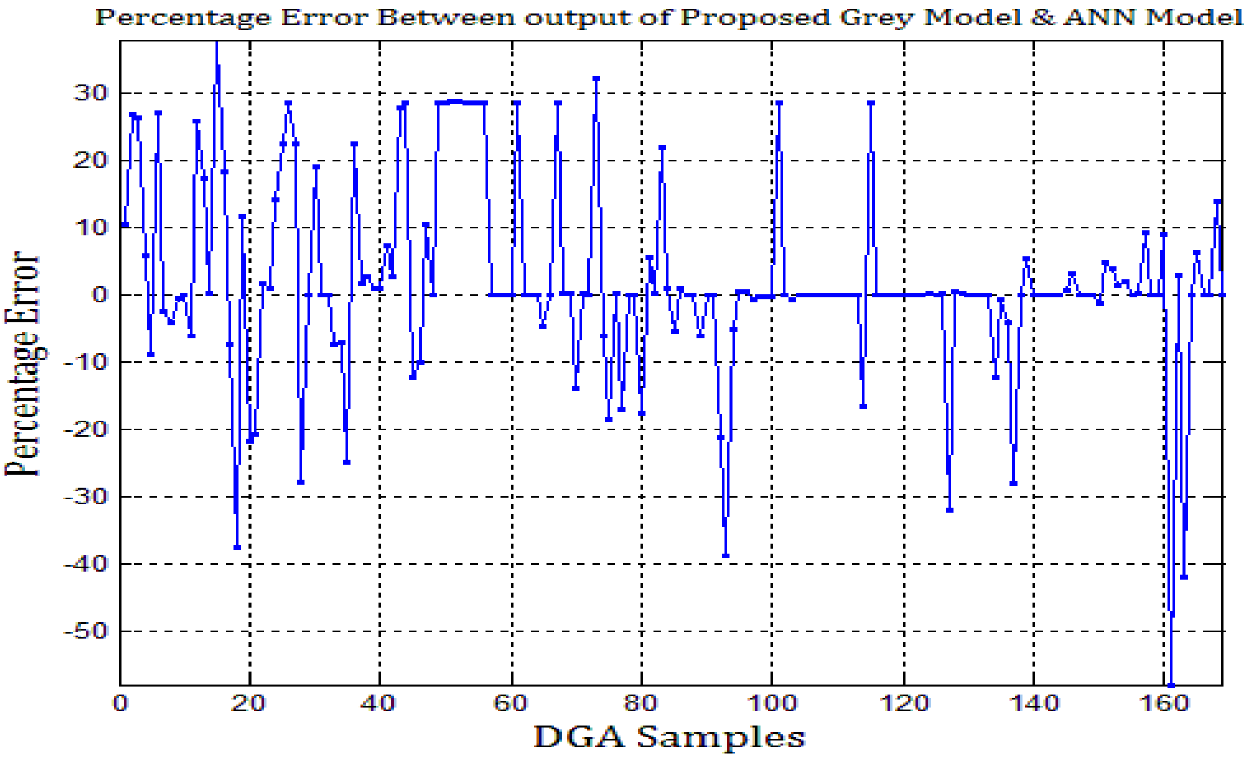

Fig. 3 **Graph of Percentage Error**

VII. CONCLUSION

This paper introduces grey theory based ANN approach to identify the transformer state based on DGA of transformer oil. Grey analysis provides an additional tool for the state assessment of Power Transformer. The Grey Theory applied on 169 samples of DGA data. The results of proposed grey model shows that whenever the gas concentrations of DGA sample are in safe limits then the target heart degree calculated for such sample has the value in the higher range indicating *normal* state for power transformer and power transformer does not have any fault for such cases. And whenever the gas concentrations of DGA sample are beyond the safe limits then the target heart degree calculated for such samples has the value in lower range indicating *faulty* state for power transformer and one or more fault may present in power transformer for such cases. This result signifies that grey theory is very effective in identifying DGA concentrations and can efficiently provide the state assessment of power transformer. Proposed Grey Model has been validated in ANN. The target heart degree calculated from proposed grey model is compared with the output given by ANN model. Target heart degree given by ANN model is close to the target heart degree calculated from proposed grey model. The ANN model results shows certain degree of success is there to validate benchmark of Proposed Grey Model.

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