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Transformer Oil Diagnostic Tests Analysis using Statistical Correlation Technique

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Abstract

This research study presents a real time data analysis on the diagnostic tests of four different service transformers by using a statistical correlation technique. Transformers are essentially passive devices that supply desired voltage at a specified frequency. Transformer oil performs two different functions within all power transformers: insulation and cooling. The quality of the transformer oil depends on the performance of this continuously working equipment. Hence it is required to conduct a concurrent scheduled as well as unscheduled diagnostic tests. The proposed analysis has considered the dielectric strength or breakdown voltage, moisture or water content, acidity or neutralization number, interfacial tension along with dissolved gas analysis diagnostic tests. Here, the statistical analysis has been performed by using correlation tests and the final results predict the linear correlation among diagnostic tests.

Keywords: Transformer oil, BDV, WC, NN, DGA

1. Introduction

Transformer is a static continuously working electromagnetic device, which is extensively used in a power system to step up/down the voltage at a rated frequency based on the requirement of utilities and electricity supply companies. Power transformers provide an intermediate link for any electrical transmission or distribution network [1]. The power transformers consist of conduction parts, cooling and insulation parts, protection devices and enclosures along with other miscellaneous components. The mineral oil extracted from the crude petroleum is composed of complex molecules of carbon and hydrogen, which perform the cooling and insulation process in the interior conduction parts the transformer [2 - 4]. The

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electrical load carrying capability as well as physical size of the transformer decides the necessary amount of oil to be filled in an oil immersed transformers. A distribution system transformer rated at 25 kVA requires approximately 20 gallons (1 US gallon = 3.785 Liters) of insulating oil. Similarly, a unit for transmission of power rated at or above 400 MVA needs more than 10,000 gallons of oil [5].

The classification transformer units required for performing replacement or rehabilitation depends on the age of the equipment. Physical ageing process mainly depends on the structural strength, design, stress, insulating and thermal properties of materials [6-9]. The actual life of a transformer is determined by the maintenance, and monitoring of operating states of transformers under different load conditions. The projected lifespan of a power transformer is about 35-45 years [10]. The primary objective of the proposed research study is to analyze and classify the transformer oil diagnostic tests into four different phases in service transformers by using the Statistical Correlation Technique (SCT). Dielectric strength or breakdown voltage (BDV), moisture/water content (WC), acidity/neutralization number (NN), interfacial tension (IFT) and dissolved gas analysis (DGA) diagnostic tests are considered here to assess the transformer oil.

This paper is organized as follows: section 2 explains the diagnostic tests, section 3 describes the SCT, section 4 furnishes the comprehensive results and discussion, and section 5 concludes the proposed research work.

2. Diagnostic Tests

Diagnostic tests are performed for all transformers in a periodic basis to identify the incipient faults in transformer. These diagnostic tests procedures are based on the international standards released by IEEE, IEC, ASTM, IS etc. The user can select the equipment for the tests according to these standards. The proposed study considers BDV, WC, NN and IFT diagnostic tests based on IS 335 (1993) as well as IS 1866 (2000) to assess the characteristic behavior of a transformer oil [11-12].

2.1 Dielectric Strength or Breakdown Voltage (BDV)

The dielectric strength of insulating oil is a degree of oil capacity to withstand the electrical stress without any failure. The test involves applying an AC voltage at an ordered rate to two electrodes immersed in the insulating oil with a specified gap distance. Once the current arcs across this gap, the voltage recorded at that instant will be considered as the dielectric strength or breakdown strength of that fluid. The dielectric strength of the transformer oil has been fundamentally reduced to a greater degree with an increase in the contaminants such as water, sediment, sludge, and their combination. Fresh oil possess a characteristically high dielectric strength but this does not necessarily indicate the absence of all contaminates since it may merely indicate that the amount of contaminants present between the electrodes is not large enough to affect the average breakdown voltage of the liquid [11-12].

2.2 Moisture or Water Content (WC)

Deterioration of insulating material within the oil immersed transformers create moisture or water. The appearance of the oil remains unchanged if only less water content is observed and hence its existence cannot be determined through inspection. Dissolved water intends to be discovered by chemical or physical experimental methods. It may or may not affect the electrical properties of the oil. The solubility of water in used/unused transformer oil increases with an increase in the temperature in addition to neutralization value. Small temperature changes will significantly modify the water content of the oil but only slightly that of insulated paper. High water content accelerates the chemical deterioration of insulating paper and is indicative of undesirable operating conditions or maintenance requiring correction [11-12].

2.3 Acidity or Neutralization Number (NN)

A measure of potassium hydroxide (KOH) in milligrams (mg) is required to neutralize the acid in one gram of transformer oil is called Acidity. Acids are formed in the oil due to its decomposition as well as oxidation products. It may also have generated from external sources such as atmospheric contaminations like varnish, paint, or other foreign matter [11-12]. The quantity of alkaline or acidic material present in oil is measured from neutralization number (NN). The NN is noticed as an indicator of nitration, oxidation and contamination. Fresh transformer oil is eventually free from acids. The acidity of oil in a transformer must never be allowed to go beyond or to be maintained within 0.25 mg KOH/gm of oil [13].

2.4 Interfacial Tension (IFT)

Interfacial Tension (IFT) measures the tension at the interface between two liquids (oil and water) which do not mix, and is expressed in dyne/cm (1dyne/cm = 1 x 10^{-3} N/m). The test is sensitive to the presence of oil decay products and soluble polar contaminants from solid insulating materials. It is highly recommended to reclaim the oil when the IFT decreases down to 25 dynes per centimeter to prevent sludge formation. The IFT test is the commanding tool used to prevent the sludge as well as to determine the remnant life of the transformer before the requirements of maintenance [11-12].

2.5 Dissolved Gas Analysis (DGA)

Dissolved Gas Analysis (DGA) [14-15] is one of the earliest proved accuracy methods to find the incipient faults in the power transformer. The complex mixtures of hydrocarbon oil is used as an insulating and cooling medium will be decomposed to release oil due to numerous stresses on the liquid. The gas fault occurred in the transformer oil modifies the chemical structure of the oil. The released gasses dissolved into the oil leads to improper operation of the equipment insulation and cooling. The main gases formed by decomposition of oil and paper are hydrogen (H_2), methane (CH_4) , ethane (C_2H_6) , ethylene (C_2H_4), acetylene (C_2H_2), carbon dioxide (CO_2) and carbon monoxide (CO).

3. Proposed Method

A real time diagnostic test exemplifies the condition of transformer oil. In this section, the data analysis is performed on real time transformer oil diagnostic tests through SCT. The diagnostic tests experiments such as BDV, WC, NN and IFT was conducted at the research lab of Karnataka Power Transmission Corporation Limited (KPTCL). The experimental results data of about 5 years with 15 experiments of four in service transformer is collected from KPTCL. These obtained data is tabularized in table 1. Figure 1 illustrates the workflow of proposed method.

3.1 Statistical Correlation Test – Analysis I

Correlation analysis is a statistical evaluation method to determine the strength of a relationship between two variables. This analysis may be useful to understand the possible influences between variables. Pearson's product-moment coefficient (r) is commonly used in correlation analysis and its ranges between -1 and 1. This method determines the apparent connection as well as measures linear relationship between variables [16-19]. Table 2 demonstrates the correlation between the different diagnostic tests such as BDV & WC, BDV & NN, BDV & IFT, WC & NN, WC & IFT as well as NN & IFT respectively.

Table 1. Real time diagnostic test data of four in service transformers

Transformer-1				**Transformer-2**			
BDV (kV)	***WC (PPM)***	***NN (mg KOH / gm)***	***IFT (Dynes/ cm)***	***BDV (kV)***	***WC (PPM)***	***NN (mg KOH / gm)***	***IFT (Dynes/ cm)***
42	19	0.05	35	30	30	0.05	35
50	12	0.05	35	47	21	0.05	35
41	16	0.05	35	39	19	0.05	35
35	24	0.05	35	48	14	0.05	35
39	14	0.05	30	46	30	0.05	35
50	20	0.05	35	24	26	0.05	30
75	2	0.05	35	42	15	0.05	30
63	4	0.05	35	45	20	0.05	35
38	13	0.05	35	56	19	0.05	35
13	12	0.05	35	16	60	0.05	35
50	18	0.05	35	47	39	0.05	35
56	18	0.05	35	42	40	0.1	30
62	11	0.05	30	50	28	0.05	35
52	18	0.05	35	43	32	0.05	35
48	22	0.05	35	37	49	0.05	35
Transformer-3				**Transformer-4**			
BDV (kV)	***WC (PPM)***	***NN (mg KOH / gm)***	***IFT (Dynes / cm)***	***BDV (kV)***	***WC (PPM)***	***NN (mg KOH / gm)***	***IFT (Dynes / cm)***
23	43	0.05	35	15	20	0.05	35
50	9	0.05	30	55	25	0.05	35
40	22	0.05	35	22	48	0.05	25
20	24	0.05	35	45	38	0.05	35
30	23	0.05	35	26	57	0.05	35
35	15	0.05	35	17	50	0.05	35
56	14	0.05	35	24	45	0.05	35
43	10	0.05	35	70	20	0.05	35
67	14	0.05	30	40	40	0.05	25
35	20	0.05	35	45	36	0.05	35
48	24	0.05	35	33	54	0.05	35
33	22	0.05	35	17	54	0.05	35
40	15	0.05	35	33	87	0.05	35
37	37	0.05	35	18	52	0.05	35
52	44	0.05	35	65	28	0.05	35

Table 2. Correlation analysis of between different diagnostic tests

Sl. No	**Correlation Between**	**Equipment**	**R^2**	**Linear Trend Equation**	**Correlation coefficient (r)**	**Correlation Category**
1	BDV & WC	Transformer-1	0.191	-1.024x + 62.83	-0.4371	Weak correlation
		Transformer-2	0.318	-0.453x + 54.17	-0.5646	Moderate correlation

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		Transformer-3	0.11	-0.376x + 49.04	-0.33177	Weak correlation
		Transformer-4	0.231	-0.495x + 56.60	-0.48156	Moderate correlation
2	BDV & WC	Transformer-1	-3.00E-01	764.4x + 9.379	1.02E-16	Weak correlation
		Transformer-2	0.001	25.71x + 39.42	0.031772	Weak correlation
		Transformer-3	-1.00E-01	133.3x + 33.93	1.18E-16	Weak correlation
		Transformer-4	-1.00E-01	595.5x + 5.222	0	Weak correlation
3	BDV & WC	Transformer-1	0.006	-0.669x + 70.57	-0.08181	Weak correlation
		Transformer-2	0.056	1.2x	0.23776	Weak correlation
		Transformer-3	0.337	-4.130x + 182.4	-0.58058	Moderate correlation
		Transformer-4	0.008	0.461x + 19.46	0.090926	Weak correlation
4	BDV & WC	Transformer-1	-3.00E-01	103.7x + 9.680	7.99E-17	Weak correlation
		Transformer-2	0.05	225.7x + 17.42	0.224163	Weak correlation
		Transformer-3	-1.00E-01	142.2x + 15.28	-1.30E-16	Weak correlation
		Transformer-4	-8.00E-01	160x + 35.60	8.47E-17	Weak correlation
5	BDV & WC	Transformer-1	0.024	0.546x - 3.884	0.156502	Weak correlation
		Transformer-2	0.009	0.616x + 8.5	0.098207	Weak correlation
		Transformer-3	0.161	2.515x - 63.96	0.401645	Weak correlation
		Transformer-4	9.00E-05	-0.046x + 45.15	-0.00936	Weak correlation
6	BDV & WC	Transformer-1	-2.00E-01	0.05	1.39E-15	Weak correlation
		Transformer-2	0.285	-0.003x + 0.166	-0.53452	Moderate correlation
		Transformer-3	-2.00E-01	0.05	1.39E-15	Weak correlation
		Transformer-4	-5.00E-01	0.05	-7.00E-16	Weak correlation

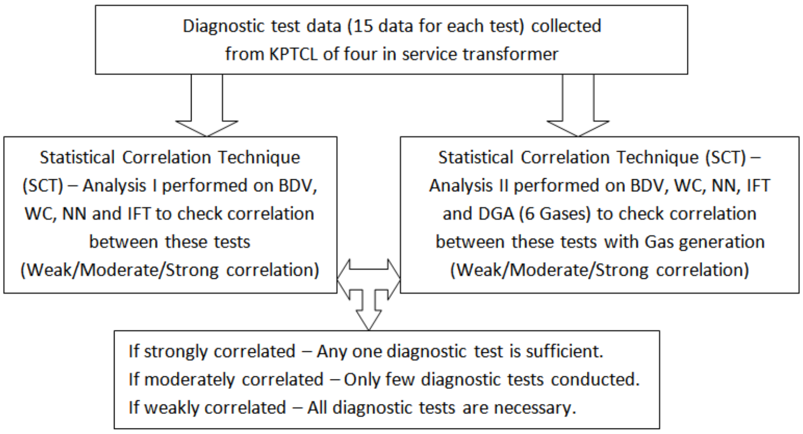
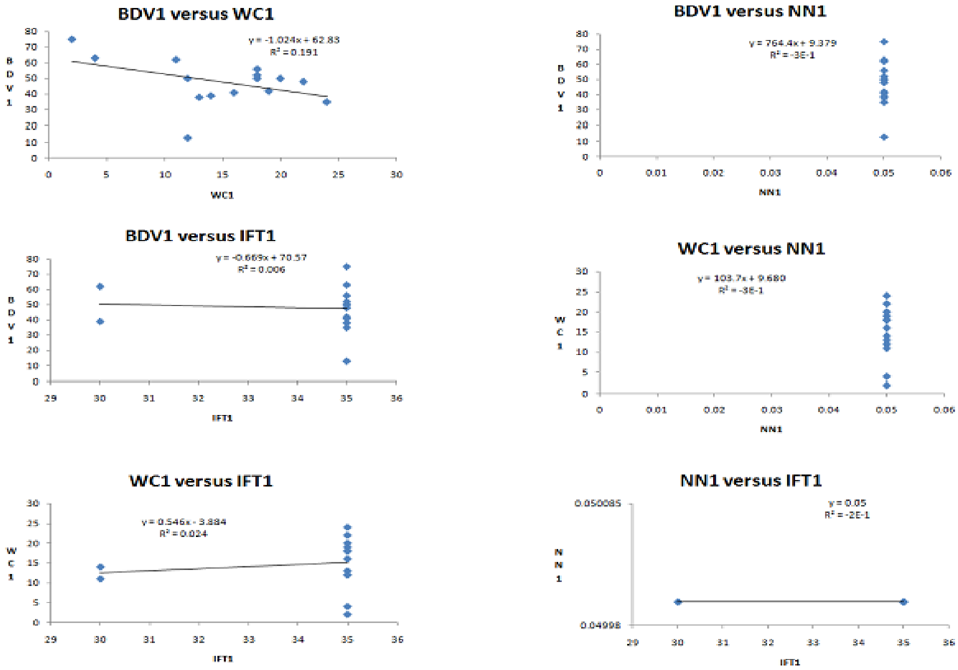


Figure 1. Block diagram representing methodology of proposed method

Table 3. DGA Data of transformer 1

Sl. No.	Dissolved gas concentrations in ppm						
	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO_2	CO
1	37	7	10	4	0	1440	392
2	37	4	7	5	0	975	281
3	40	3	4	2	0	938	327
4	39	14	12	2	0	1390	345
5	41	11	9	2	0	807	253
6	37	8	3	4	0	526	237
7	45	12	4	9	0	3489	473

8	43	3	4	12	0	1917	465
9	39	5	9	4	0	2654	433
10	35	6	8	4	0	837	433
11	40	9	8	5	0	3345	269
12	38	4	6	2	0	4270	391
13	43	7	7	6	0	3721	554
14	36	13	7	1	0	2987	439
15	39	9	1	2	0	3765	235



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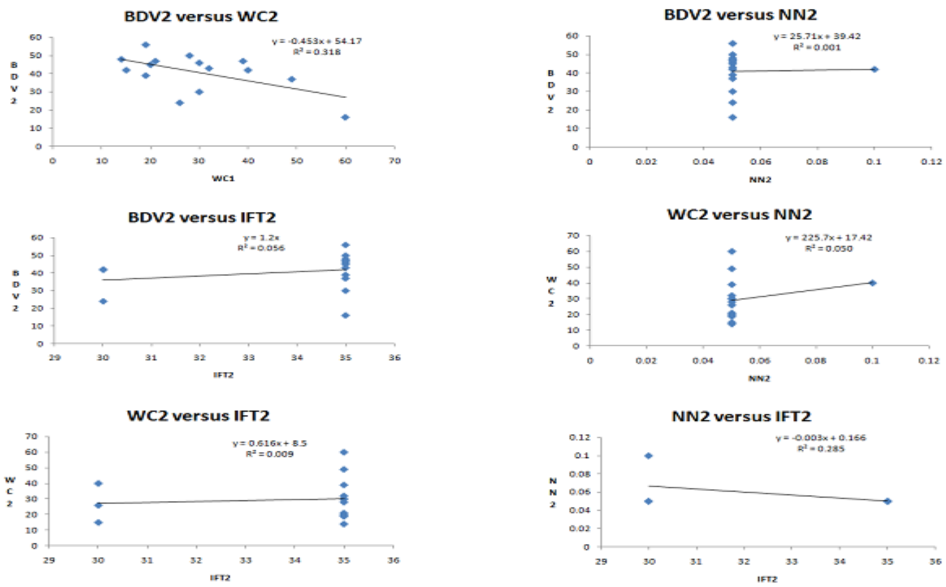
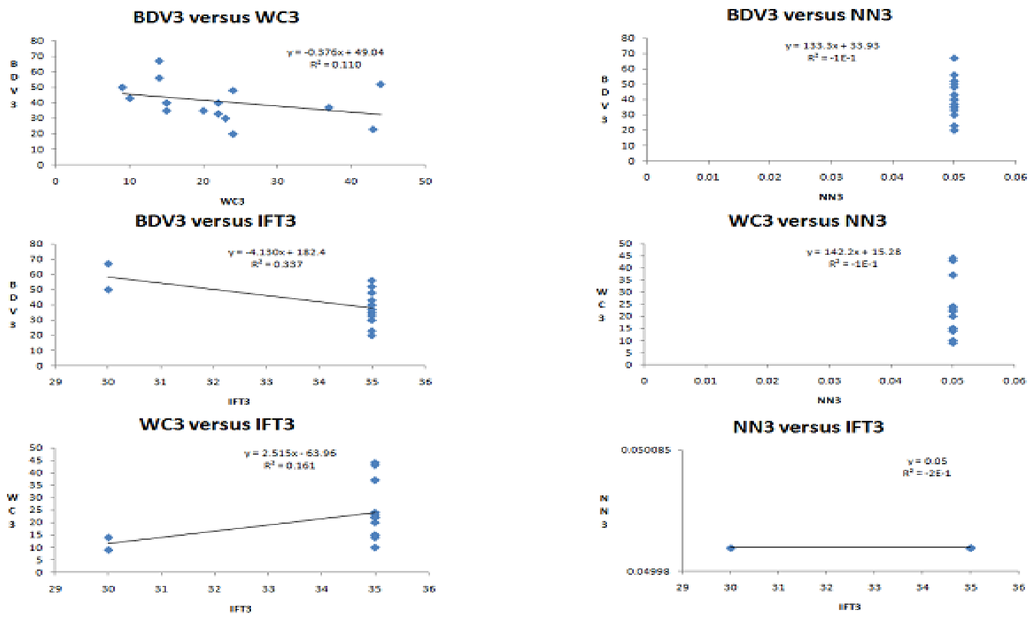


(b)

Figure 2. Scatter plot of correlation analysis between diagnostic tests for (a) Transformer-1 (b) Transformer-2



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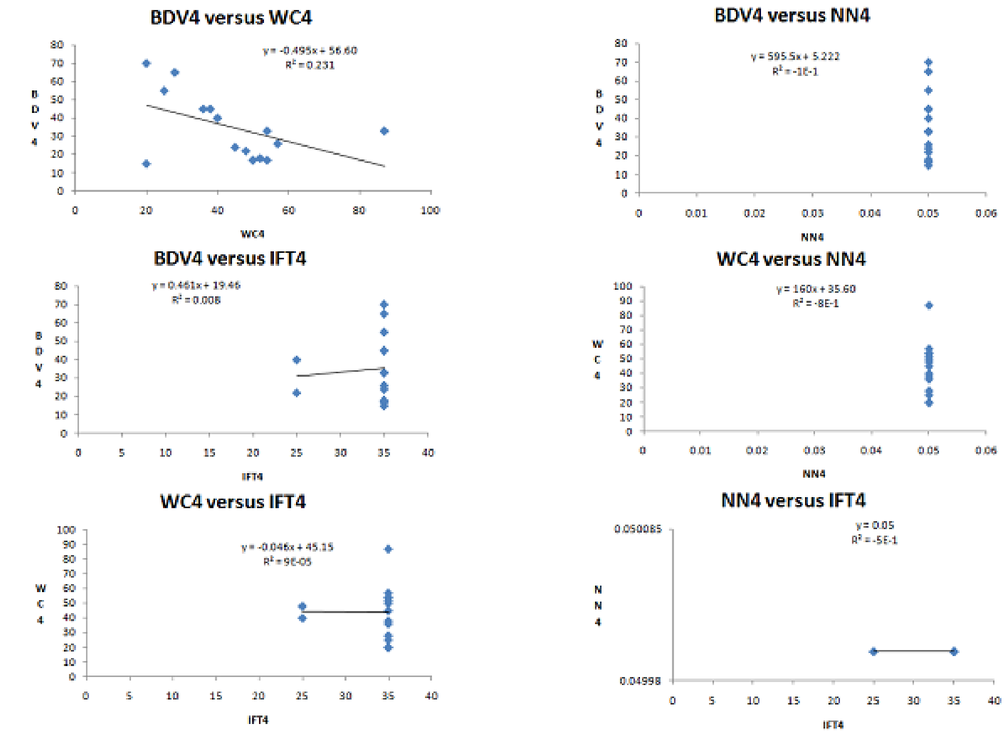

(b)

Figure 3. Scatter plot of correlation analysis between diagnostic tests for (a) Transformer-3 (b) Transformer-4

Table 4. DGA Data of Transformer-2

Sl. No.	Dissolved gas concentrations in ppm						
	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO_2	CO
1	40	14	7	3	0	3764	221
2	39	9	6	3	0	2890	298
3	35	10	1	5	0	2377	343

4	35	1	7	7	0	3495	427
5	40	4	3	2	0	1976	288
6	42	13	5	2	0	1275	259
7	35	11	5	2	0	1754	391
8	33	7	5	6	0	2679	233
9	37	5	2	5	0	1349	457
10	43	4	7	1	0.03	1897	468
11	43	1	1	1	0	2241	248
12	45	6	3	4	0	3981	372
13	39	5	3	7	0	1789	350
14	28	8	5	4	0	2334	451
15	40	3	8	1	0	2993	212

Table 5. DGA Data of Transformer-3

Sl. No.	Dissolved gas concentrations in ppm						
	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO_2	CO
1	48	9	7	2	0	1893	273
2	39	15	5	5	0	2883	299
3	45	7	5	3	0	1239	354
4	45	4	4	3	0	1768	255
5	40	6	1	1	0.09	2439	231
6	32	11	9	7	0	2685	332
7	35	12	6	5	0	2987	369
8	43	8	5	6	0	3450	241
9	41	4	3	2	0	3714	437
10	40	2	3	2	0	2376	376
11	40	10	1	2	0	2765	391
12	44	5	7	5	0	4321	286
13	43	9	7	3	0	3998	348
14	46	13	3	1	0	4521	247
15	44	11	5	1	0	5487	451

This is achieved by using a scatter plot and choosing linear trend line for experimental diagnostic data using excel software. Linear equation is obtained with the relationship linear trend line between the variables. The relationships between the diagnostic tests are drawn with the determination of R^2 as well as correlation coefficient r. R^2 illustrates the data near or for away from trend line.

Similarly, the values of r describes that the diagnostic tests are either moderate correlated or weak correlated. Fig. 2 and Fig. 3 is the diagrammatic representation of correlation between the diagnostic tests of individual transformers. Fig. 2 (a) explore there is weak correlation between the diagnostic tests of transformer-1. Fig. 2 (b) illustrates the moderate correlation between BDV & WC, IFT & NN, and weak correlation between other tests of transformer-2.

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Fig. 3(a) demonstrates the moderate correlation between BDV & IFT and weak correlation between other diagnostic tests of transformer-3. Similarly Figure 3(b) explains moderate correlation between BDV & WC and weak relationship among the remaining tests.

Table 6. DGA Data of Transformer-4

Sl.No.	Dissolved gas concentrations in ppm						
	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO_2	CO
1	37	4	14	3	0	2987	432
2	37	10	19	2	0	2576	379
3	40	7	8	4	0	3447	335
4	39	6	1	1	0	1765	278
5	41	8	1	1	0	2567	253
6	37	11	9	2	0	3723	345
7	45	13	7	2	0	3541	489
8	43	9	3	4	0	3093	237
9	39	5	2	2	0	2788	385
10	35	2	7	1	0	2352	290
11	40	6	2	3	0	1964	336
12	38	7	3	5	0	2817	229
13	43	11	3	1	0	2249	255
14	36	9	1	4	0	1789	361
15	39	10	1	1	0	2557	279

3.1.1 Statistical Correlation Test – Analysis II

Table 3 to 6 shows the DGA data. Table 7 to table 10 demonstrates the correlation between the DGA, BDV, WC, NN and IFT for four in-service transformers. The Table 2 implies the correlation category with correlation between the two diagnostic tests using correlation coefficients. But in the table 7 to 10, the correlation co-efficient(r) evaluated between the six gases of DGA such as H_2, CH_4, C_2H_6, C_2H_4, and CO_2 along with CO and BDV, WC, NN and IFT.

The C_2H_2 gas of DGA not considered in correlation analysis since except two values of C_2H_2 remaining values are zero. The strong correlated value (r between 0.8-0.9 is) -0.815 among all the correlation values is between ethane gas C2H6 and water content WC in the transformer oil of transformer 1. There is no value of r between 0.7 - 0.8. Correspondingly there are values or r between 0.6 - 0.7, 0.5 - 0.6, 0.4 - 0.5, 0.3 - 0.4, 0.2 - 0.3 and 0.0 - 0.2. In correlation analysis, if the r value lies below 0.5 is assumed to be weakly correlated. Similarly the r value from 0.5 to 0.7 is moderately correlated, 0.7 to 0.9 is strongly correlated and finally 0.9 to 1.0 is strongly correlated [16-19].

Table 7. Correlation between DGA, BDV, WC, NN & IFT of tranformer-1

	H_2	CH_4	C_2H_4	C_2H_6	CO_2	CO	BDV	WC	NN	IFT
H_2	1									
CH_4	0.072	1								
C_2H_4	-0.236	0.268	1							
C_2H_6	0.625	-0.271	-0.249	1						
CO_2	0.352	0.117	-0.230	0.082	1					
CO	0.329	-0.099	0.157	0.450	0.360	1				
BDV	0.671	0.048	-0.467	0.534	0.562	0.265	1			
WC	-0.609	0.274	0.214	-0.815	-0.076	-0.573	-0.437	1		
NN	0.000	0.000	0.000	0.000	0.000	0.000	0.000	8E-17	1	
IFT	-0.394	-0.150	-0.193	0.037	-0.019	-0.144	-0.082	2E-01	1E-15	1

Table 8. Correlation between DGA, BDV, WC, NN & IFT of transformer - 2

	H_2	CH_4	C_2H_4	C_2H_6	CO_2	CO	BDV	WC	NN	IFT
H_2	1									
CH_4	-0.150	1								
C_2H_4	-0.057	0.110	1							
C_2H_6	-0.479	-0.075	-0.184	1						
CO_2	0.096	-0.046	0.352	0.165	1					
CO	-0.289	-0.209	-0.086	0.285	-0.230	1				
BDV	-0.356	-0.370	-0.472	0.533	0.022	0.094	1			
WC	0.546	-0.330	0.236	-0.593	0.088	-0.039	-0.565	1		
NN	0.416	-0.050	-0.187	0.061	0.505	0.114	0.032	0.224	1	
IFT	-0.277	-0.418	0.046	0.214	0.072	-0.035	0.238	0.098	-0.535	1

Table 9. Correlation between DGA, BDV, WC, NN & IFT of transformer - 3

	H_2	CH_4	C_2H_4	C_2H_6	CO_2	CO	BDV	WC	NN	IFT
H_2	1									
CH_4	-0.223	1								
C_2H_4	-0.143	0.249	1							
C_2H_6	-0.534	0.216	0.660	1						
CO_2	0.085	0.281	0.075	-0.112	1					
CO	-0.259	-0.027	-0.021	-0.184	0.267	1				
BDV	-0.356	0.274	-0.149	0.042	0.428	0.699	1			
WC	0.599	0.081	-0.086	-0.657	0.209	0.017	-0.332	1		
NN	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-1E-16	1	
IFT	0.160	-0.120	0.130	-0.063	-0.069	-0.240	-0.581	4E-01	1E-15	1

Table 10. Correlation between DGA, BDV, WC, NN & IFT of transformer - 4

	H_2	CH_4	C_2H_4	C_2H_6	CO_2	CO	BDV	WC	NN	IFT
H_2	1									
CH_4	0.542	1								
C_2H_4	-0.292	0.022	1							
C_2H_6	-0.068	-0.057	0.036	1						
CO_2	0.261	0.315	0.407	0.216	1					
CO	-0.002	0.126	0.513	0.009	0.331	1				

BDV	0.139	0.031	-0.081	-0.311	-0.207	-0.343	1			
WC	0.286	0.276	-0.407	-0.096	-0.192	-0.252	-0.482	1		
NN	0.000	0.000	0.000	0.000	0.000	0.000	0.000	8E-17	1	
IFT	-0.034	0.255	0.030	-0.180	-0.291	-0.186	0.091	-9E-03	-7E-16	1

(±) 0.0-0.2		(±) 0.5-0.6	
(±) 0.2-0.3		(±) 0.6-0.7	
(±) 0.3-0.4		(±) 0.7-0.8	
(±) 0.4-0.5		(±) 0.8-0.9	

To identify the weak, moderate and strong correlation different colors were used in table 7 to 10. In transformer 1(table 7), WC and C_2H_6 are strongly correlated, H_2 and C_2H_6, H_2 and BDV, H_2 and WC, BDV and C_2H_6, BDV and CO_2, WC and CO are moderately correlated, and remaining weakly correlated. In transformer 2 (table 8), BDV and C_2H_6, WC and H_2, WC and C_2H_6, WC and BDV, NN and CO_2, NN and IFT are moderately correlated, and remaining weakly correlated.

In transformer 3(table 9), H_2 and C_2H_6, C_2H_6 and C_2H_4, BDV and CO, WC and H_2, WC and C_2H_6, IFT and BDV are moderately correlated, and remaining are weakly correlated. Similarly in transformer 4(table 10) H_2 and CH_4, C_2H_4 and CO are moderately correlated, remaining are weakly correlated. The r values imply that the BDV, WC as well as DGA were moderately correlated leading to changes in the characteristics of the oil in future.

This correlation analysis exemplifies the relationship between the characteristics of diagnostic tests. This method is completely a quantitative procedure. The correlation analysis indicates the relationship between the diagnostic tests. Hence it can be proved that this method is superior in the quantitative analysis when compared with existing methods for assessing the quality of transformer oil since each test included in the analysis. Also six gasses of DGA inclusion is a new method in the assessment of transformer oil.

4. Conclusion

In this paper, SCT is used as a quantitative method for the analysis of transformer oil through the real time diagnostic tests. Moreover, SCT categorizes the relationship among different diagnostics tests. The correlation analysis illustrates the weak or moderate correlation between diagnostic tests. In addition, R^2 values exemplify the percentage values of correlation among the different diagnostic tests.

The correlation analysis-I and II performed to quantify the correlated values between diagnostic tests. These correlation study leads to a new assessment technique for analyzing the quality of transformer oil. If there is a strong correlation between diagnostic tests, then only one test is required to determine the quality of oil. Furthermore, moderate correlation directs only the performance of necessary diagnostic tests. Similarly, weak correlation guides to perform all diagnostic tests. If found any fault in any one diagnostic test then proper action of filtering the oil or replacement should be carried out. This action enhances the life span of transformer. Further, the proposed method can be used as statistical characterization of monitoring the system malfunction due to the variation of chemical bonding in transformer oil.

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Transformer Data:

The four in-service transformers under consideration in this paper are

Transformer 1: 100MVA, 220 / 110 KV, CGL-Transformer
Transformer 2: 20MVA, 110 / 33 KV EMCO-Transformer
Transformer 3: 12.5MVA, 66 / 11 KV RIMA-Transformer
Transformer 4: 10MVA, 110 / 33 KV NGEF-Transformer

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