Transformer Winding Insulation Measurement Using Phase Difference Technique

Prabir Ranjan Kasari, Prashanta Saha, Abanishwar Chakrabarti, Bikram Das

***Abstract:** This paper describes the condition monitoring of Transformer winding. Condition Monitoring means capable to predict health condition of the electrical machine. A successful continuous condition monitoring scheme for electrical machines offers significant advantages, since it would be capable of providing adequate warning of failures of a variety of its components and would enable maintenance to be scheduled most effectively. In diagnosing faults in electrical machines, research has focused on parameters such as, insulation, capacitance, temperature, phase angle etc. In this paper a test procedure has been establish to determine the phase difference accurately. Based on this phase difference, the capacitance of the transformer winding has been calculated. The value of the capacitance basically indicates the insulation of the transformer winding. Accelerated life testing arrangement conducted to transformer winding, from this accelerated life test, approximate prediction of life of insulating material has been analysed. As the paper describes the continuous monitoring of transformer winding, so the ageing and the winding deterioration of transformer can be detected.*

***Keywords:** Condition monitoring, predictive maintenance of machine, insulation of transformer winding, dissolve gas analysis, current signature analysis.*

I. INTRODUCTION

The history of fault diagnosis, condition monitoring and protection is as old as technical devices themselves. Generally online condition monitoring and diagnosis requires the sensing and analysis of such signals that contain specific information (symptoms), which is characteristic of the degradation process, problem, or fault to be detected. Various factors need to be considered when selecting the most appropriate monitoring technique for application in an industrial environment [1].The most important factors are listed below: 1. The sensor should be non-invasive. 2. The sensor and instrumentation system must be reliable. 3. The diagnosis must be reliable. 4. The severity of the problem should be qualified 5. Ideally, an estimation of the remaining run-life should be given. 6. Ideally, a prediction of the fundamental causes of the fault should be provided via online information from sensors etc.

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II. CURRENT MONITORING – DRAWBACKS

Taking into consideration the following potential drawbacks of a condition monitoring system relying only on current monitoring, the motivation for approaching and relying on additional fault indicators seems to be clear and realistic:

For multiple faults or different varieties of drive schemes, MCSA may not provide enough ability to discriminate between different faults, since such abnormalities and time harmonics may end up generating similar signatures.

The current spectrum is influenced not only by fault conditions but also by other factors, including the supply, static and dynamic load conditions, noise, machine geometry, and fault conditions, and these conditions may lead to errors in fault detection.

III. INSULATION MEASUREMENT AND LIFE ESTIMATION TECHNIQUE

Condition monitoring of electrical equipment is becoming popular. Some of most widely used monitoring technique includes current signature analysis, vibration analysis, axial flux analysis, partial discharge measurement, dissolve gas analysis. The most important factor behind the wide spread used of monitoring technique has been the increase in productivity with reduction in stand by capacity. Critical application, where unplanned shutdown is not permitted, requires redundancy. Condition monitoring may be an alternative to such problems. The machines, which have run for its useful life and still can be used, are often used with monitoring technique to avoid unplanned shutdown.

They represent available requires transducer like vibration accelerometer search coil, high frequency CT etc. and the success of the technique depends on transducer. Winding fault causes approximately 20% failure of the rotating machine [2].

This paper describes a technique for insulation condition monitoring and residual life estimation of winding insulation.

Now to relate the life of the insulation with the phase difference we require

a. Determination of phase difference
b. To analysis the accelerating life testing of winding
c. To estimate the life of the winding.

A. Determination of phase difference:

The aim of this project is to monitor the insulation of the transformer winding which is highly insulated and any damage in the winding insulation will led to huge problem in the transformer as well as the whole system. Now, if we could manage to get alarm or any sort which will indicate the condition of the winding insulation then it will be possible to take some remedial steps from further damage.

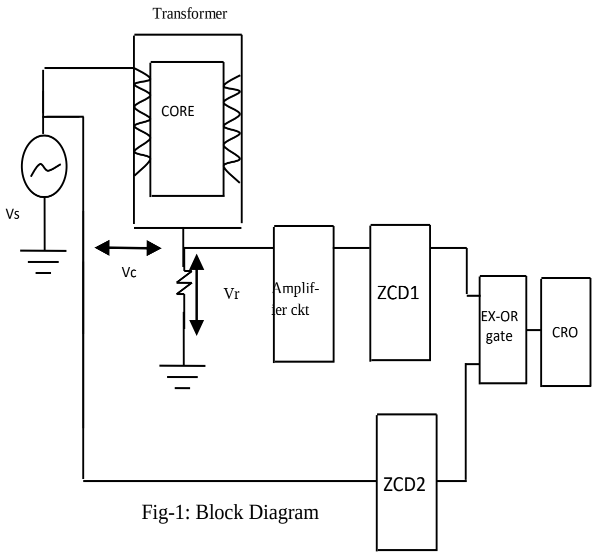

Fig-1: Block Diagram

IV. THE BLOCK DIAGRAM AND ITS COMPONENTS

A. Amplifier

This is usually employed for voltage amplification. Figure-2 shows three stage of an R-C coupled amplifier.
The emitter bypass capacitor offer low reactance path to the signal. Without it the voltage gain of each stage would be lost. The coupling capacitor Cc transmits AC signal but block DC. This prevents DC interference between various stages and the shifting of operating point.

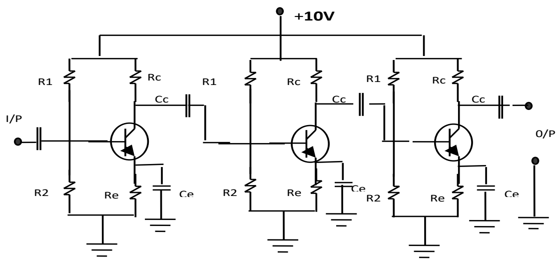

Fig-2: Amplifier Circuit

When AC signal is applied to the base of the transistor it appears in the applied form across its collector load Rc. The amplified signal developed across Rc is given to base of next stage through coupling capacitor Cc. The second stage does further amplification of the signal. In this way, the cascade stages amplify the signal and the overall gain is considerably increased.

B. Zero crossing detectors

The basic comparator in fig-3 can be used as the zero crossing detector provided that V_{ref} is set to zero(V_{ref}=0 V). In some application the input V_{in} may be a slowly changing wave form, that is a low frequency signal. Therefore it will take V_{in} more time to cross zero volts, therefore, V_0 may not switch quickly from one saturation voltage to the other. The output V_0 may fluctuate between saturation voltages $+V_{set}$ and $-V_{set}$, detecting zero reference crossing for noise voltages as well as V_{in}.

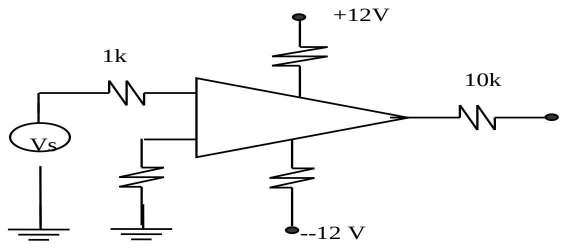

Fig-3: Zero crossing Detector

C. X-OR gate

From the X-OR gate application we can compare two digital signals, the truth table depicts that same input will results zero (0) and different input will led to give one (1). The implementation of this logic in this project is to find out the phase difference between the two signals. The execution circuit is given below.

D. Opto-coupler:

It will optically isolate the low-voltage circuitry from the high voltage circuit and thus provide protection to the low-voltage circuit and stops reverse flow of power to the low-voltage circuit.

V. DEPICTION OF THE BLOCK DIAGRAM

The insulation of the winding is the important aspect of transformer as it will prevent from short circuit and provide other important safety. Insulating material acts as dielectric material of the capacitor. In Figure-1 Vs is the source voltage and Vc is the voltage across the capacitor. Since the current signal which range from nano-ampere or microampere so we have connected a high resistance, to get signal in term of voltage i.e Vr.

A. Mathematical Expression:

$$\frac{(X_L - X_c)}{R} = \tan\varphi \qquad (1)$$

$$X_L - X_c = (\tan\varphi \times R) \qquad (2)$$

$$X_c = X_L + (\tan\varphi \times R) \qquad (3)$$

$$C = \frac{1}{2\pi f\left[x_L + (R \times \tan\varphi)\right]} \qquad (4)$$

The block diagram arrangement is to calculate the capacitance in terms of the phase angle. Firstly from function generator high frequency voltage is supplied to transformer by shorting the high voltage winding terminals. To complete the circuit, another point is taken from the core of the transformer. A high resistance about 100K is connected with the core followed by grounding.

B. Process to measure the phase angle

The Voltage signal Vc is taken from the source and the current signal is taken from the drop across high resistance.

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The voltage Vr is feed to the ZCD after amplification as it is in the micro range. The two signal of Vc , Vr are connected to ZCDs and it will produce square wave which will not in same phase. The outputs of ZCDs are feed to the EX-OR Gate.

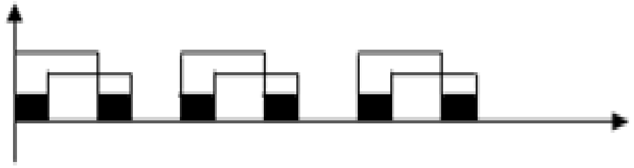

Fig-4 Ex-OR output

The figure-4 shows the EX-OR Gate output wave in the form of voltage and current signal, this is actually the phase difference between voltage and current. The change in the phase will led to know the change in the capacitance means the insulation.

C. Determination of accelerating life testing of winding

As per the Arrehnius Law the life of the insulating materials becomes half if it works 10°C more than the normally rated operating temperature means it will change rapidly if it works more than the rated temperature[3].Transformer is the important or most costly apparatus as it take 60% of capital cost of power system station. Sudden fault in transformer means the area connected to that particular station will come in shutdown condition and also damage the transformer and as well as other connected accessories with the station.

D. Process involves increasing the temperature of the winding:

The AC input signal of transformer is converted to DC by using bridge rectifier. The transformer winding will be heated up means the winding temperature will be increase due to flow of directional current in the transformer core. The rectified output is unregulated, so a capacitor is connected to the parallel to the rectified output to make it regulated DC.

Current in the circuit:

$$I_R = \frac{V_R}{R} \quad (5)$$

$$I_R = I_c \quad (6)$$

$$X_c = \frac{V_c}{I_c} \quad (7)$$

$$X_c = \frac{1}{2\pi fC} \quad (8)$$

$$C = \frac{1}{2\pi fX_c} \quad (9)$$

E. Procedure for the test

1. Measurement of primary and secondary winding resistance by V-I method.
2. The measurement of the resistance of the winding will indicates the voltage limitation of the windings.

TABLE-1 WINDING RESISTANCE TRANSFORMER-1

Primary Winding			Secondary Winding		
V	I	R	V	I	R
24.3	0.581	417	1.4	0.1435	9.75
25.5	0.061	417.5	1.5	0.153	9.8
26.5	0.0631	418.5	1.6	0.1624	9.8

TABLE-2 WINDING RESISTANCE TRANSFORMER-2

Primary Winding			Secondary Winding		
V	I	R	V	I	R
25.5	0.625	408	1.2	0.1454	8.25
26	0.0636	408.5	1.6	0.1839	8.70
27.5	0.0671	409.5	1.8	0.2033	8.85

VI. RESISTANCE OF THE TRANSFORMER WINDING AT DIFFERENT TEMPERATURE

As shown in figure we connected high voltage to the rectifier circuit to heat the winding. The resistance of the high voltage side is more compare to low voltage side. This will help us to smoothly vary the input DC voltage unlike case for the secondary winding. Since the resistance of the low voltage winding is less, therefore slightly change in the input voltage may damage the insulation of the winding instantly before any conclusion come out.

1. The transformer itself works as the load in the circuit. Total I^2Rt loss across the winding will increase temperature. The range of the temperature can varied by changing the input voltage.
2. The readings are taken after continuous heating the winding for long 4-5 hour.
3. The above steps are repeated for numbers of times for each case all most we got appropriate result in accordance to the Arrhenius law.

TABLE 3 RESISTANCE OF THREE TRANSFORMERS AFTER HEATING AT DIFFERENT TEMPERATURE

Temperat-ure in °C	Transformer-1 (Ω)	Transformer-2 (Ω)	Transformer-3 (Ω)
60	408	420	417
68	419.3728	431.7073	428.6237
76	431.3978	444.086	440.914
85	445.7778	458.8889	455.6111
92	457.6426	471.1027	467.7376
99	470.1563	483.9844	480.5273
103	477.619	491.6667	488.1548

VII. LIFE ESTIMATION

As per the Arrhenius law the life of the insulating materials becomes half if it works 10°C more than the normally rated operating temperature. The life of the insulating material changes rapidly if works more than the rated temperature. The Law $L(V)=Ce^{V/B}$ is used for life estimation of any material[15]. Here this formula will be used to calculate the life of the insulating material.

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L(v)=Life of the insulating material
V=stress level of the material
C & E= Constant parameter

$$L_1(V) = Ce^{\frac{V_1}{B}} \quad (10)$$

$$L_2(V) = Ce^{\frac{V_2}{B}} \quad (11)$$

Dividing equation(10) by equation (12)

$$\frac{L_1(V)}{L_2(V)} = \frac{e^{\frac{V_1}{B}}}{e^{\frac{V_2}{B}}} \quad (12)$$

the common term C can be cancelled out. Taking Log both sides we get,

$$\ln L_1 - \ln L_2 = \frac{V_1}{B} - \frac{V_2}{B} \quad (13)$$

$$\mathrm{B} = \frac{(V_1 - V_2)}{(\ln L_1 - \ln L_2)} \quad (14)$$

The above expression can be used to calculate the constant parameter

$$L(v) = Ce^{\frac{V}{B}}$$

$$\mathrm{C} = \frac{L(v)}{e^{\frac{V}{B}}} \quad (15)$$

From equation (4) the value of constant C can be found. Table below shows comparable study to find the value of constant that mentioned in the law.

TABLE 4. TO FIND CONSTANT B AND CONSTANT C

Life 1	Tem 1	T in Kel	Life2	Tem 2	T in Kel	Const B	Const C
240	110	383	120	120	393	-14.42	$8.12\mathrm{x}10^{13}$
480	100	373	240	110	383	-14.42	$8.12\mathrm{x}10^{13}$

TABLE 5 LIFE OF ISULATION

Tem (°C)	Tem (K)	V/B	e(v/b)	Life=C*e(v/b)	Days	Years
60	333	-23.08	$9.45\mathrm{x}10^{-11}$	7680	960	2.63013
70	343	-23.77	$4.72\mathrm{x}10^{-11}$	3840	480	1.31506
80	353	-24.46	$2.36\mathrm{x}10^{-11}$	1920	240	0.65753
90	363	-25.85	$1.18\mathrm{x}10^{-11}$	960	120	0.32876
100	373	-25.85	$5.90\mathrm{x}10^{-12}$	480	60	0.16438

winding is 60° C then estimated life of insulation is near about 7680 hours or 960 days, considering 8 hours working period daily. Similarly for 70° C the life of insulation becomes just half comparing to 60° C. This way estimate the life of insulation can be estimated.

VIII. RESULTS OF AGING EXPERIMENTS

TABLE 7 THE VALUE OF CAPACITANCE OBTAINED AFTER HEATING WINDING 115°C

Time (Hr)	Vc	Vr	Ic	Xc	C(pF)
0	7.4	0.322	$3.32\mathrm{x}10^{-6}$	2229193	71.4
6	7.4	0.321	$3.30\ \mathrm{x}10^{-6}$	2236137	71.2
12	7.4	0.32	$3.29\ \mathrm{x}10^{-6}$	2243125	71
18	7.4	0.32	$3.29\ \mathrm{x}10^{-6}$	2243125	71
24	7.43	0.319	$3.28\ \mathrm{x}10^{-6}$	2259279	70.5
30	7.43	0.316	$3.25\ \mathrm{x}10^{-6}$	2280728	69.8
36	7.44	0.31	$3.19\ \mathrm{x}10^{-6}$	2328000	68.4
42	7.44	0.308	$3.17\ \mathrm{x}10^{-6}$	2343117	68
48	7.45	0.306	$3.15\ \mathrm{x}10^{-6}$	2361601	67.4
54	7.45	0.304	$3.13\ \mathrm{x}10^{-6}$	2377138	67
60	7.45	0.303	$3.12\ \mathrm{x}10^{-6}$	2384983	66.8
66	7.46	0.301	$3.10\ \mathrm{x}10^{-6}$	2404053	66.2
72	7.46	0.301	$3.10\ \mathrm{x}10^{-6}$	2404053	66.2
78	7.46	0.3	$3.09\ \mathrm{x}10^{-6}$	2412067	66
84	7.47	0.29	$2.98\ \mathrm{x}10^{-6}$	2498586	63.7

TABLE 6 THE VALUE OF CAPACITANCE OBTAINED AFTER HEATING WINDING 120°C

Time (Hr)	Vc	Vr	Ic	Xc	C(pF)
0	7.47	0.322	$3.32\mathrm{x}10^{-6}$	2250279.5	70.76
6	7.47	0.321	$3.30\ \mathrm{x}10^{-6}$	2257289.7	70.54
12	7.47	0.32	$3.29\ \mathrm{x}10^{-6}$	2264343.8	70.32
18	7.47	0.32	$3.29\ \mathrm{x}10^{-6}$	2264343.8	70.32
24	7.49	0.319	$3.28\ \mathrm{x}10^{-6}$	2277523.5	69.91
30	7.49	0.316	$3.25\ \mathrm{x}10^{-6}$	2299145.6	69.25
36	7.5	0.31	$3.19\ \mathrm{x}10^{-6}$	2346774.2	67.85
42	7.5	0.308	$3.17\ \mathrm{x}10^{-6}$	2362013	67.41
48	7.5	0.306	$3.15\ \mathrm{x}10^{-6}$	2377451	66.97
54	7.6	0.304	$3.13\ \mathrm{x}10^{-6}$	2425000	65.66
60	7.6	0.303	$3.12\ \mathrm{x}10^{-6}$	2433003.3	65.44

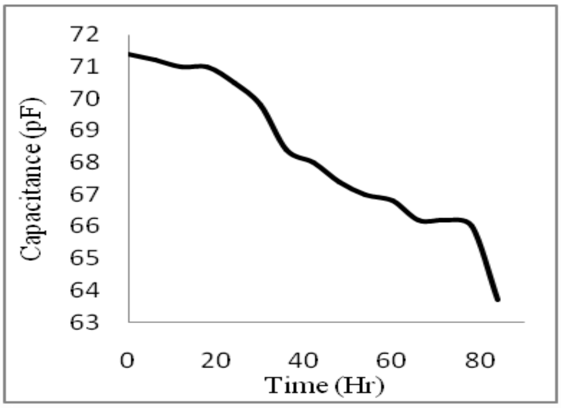

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TABLE-8 THE VALUE OF CAPACITANCE OBTAINED AFTER HEATING WINDING 110°C

Time (Hr)	Vc	Vr	Ic	Xc	C(pF)
0	7.52	0.368	3.79x10^{-6}	1980000	80.3
6	7.52	0.367	3.78 x10^{-6}	1990000	80.1
12	7.5	0.366	3.77 x10^{-6}	1990000	80.1
18	7.5	0.365	3.76 x10^{-6}	1990000	79.9
24	7.54	0.363	3.74 x10^{-6}	2020000	79
30	7.53	0.362	3.73 x10^{-6}	2020000	78.9
36	7.54	0.361	3.72 x10^{-6}	2030000	78.6
42	7.54	0.36	3.71 x10^{-6}	2030000	78.4
48	7.53	0.359	3.70 x10^{-6}	2030000	78.3
54	7.5	0.358	3.69 x10^{-6}	2030000	78.4
60	7.53	0.357	3.68 x10^{-6}	2050000	77.8
66	7.57	0.356	3.67 x10^{-6}	2060000	77.2
72	7.52	0.355	3.66 x10^{-6}	2050000	77.5
78	7.49	0.354	3.65 x10^{-6}	2050000	77.6
84	7.57	0.352	3.63 x10^{-6}	2090000	76.3
90	7.53	0.351	3.62 x10^{-6}	2080000	76.5
96	7.58	0.35	3.61 x10^{-6}	2100000	75.8
102	7.56	0.349	3.60 x10^{-6}	2100000	75.8
108	7.58	0.348	3.59 x10^{-6}	2110000	75.4
114	7.59	0.347	3.58 x10^{-6}	2120000	75.1
120	7.68	0.346	3.57 x10^{-6}	2150000	74
126	7.6	0.345	3.56 x10^{-6}	2140000	74.5
132	7.71	0.344	3.55 x10^{-6}	2180000	73.2
138	7.69	0.342	3.53 x10^{-6}	2180000	73
144	7.68	0.341	3.52 x10^{-6}	2180000	72.9
150	7.62	0.34	3.51 x10^{-6}	2170000	73.2
156	7.6	0.339	3.49 x10^{-6}	2180000	73.2
162	7.66	0.338	3.48 x10^{-6}	2200000	72.4

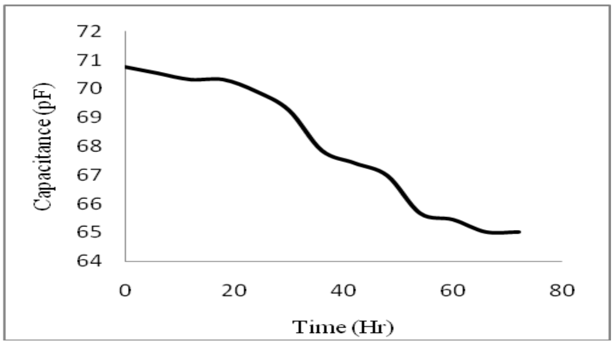

Fig 5 Deterioration of capacitance at 120°C

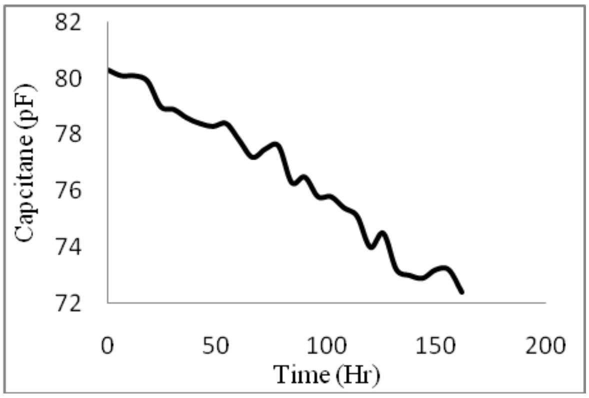

Fig 7 Deterioration of capacitance at 110°C

The Table-6, 7 and table 8 shows the experimental data. In block diagram of figure-1, shown that Vs is supply voltage,Vc is the voltage between winding to ground, Vr is the drop across the resistance which is connected between transformer core to the ground, Ic is the current flow from transformer core to the ground through resistance R, Xc is the transformer winding reactance and C is the capacitance of transformer insulation.

Table-6 shows the experimental data by applying 7.72 volt to the primary side of transformer after heating it at 120°C and due to the heating deterioration of capacitance of transformer winding takes place and this shows in figure 5. Similarly Table-7 and Table-8 shows the experimental data by applying 7.72 volt to the primary side of transformer after heating it at 115°C and 110°C respectively and correspondingly graph of figure 6 and 7 are obtained which also shows the deterioration of capacitance of transformer winding insulation with time.

IX. CONCLUSION

In this project a test procedure has been established to determine phase difference accurately. Based on this phase difference, the capacitance of the winding has been calculated. The value of the capacitance basically indicates the insulation of the winding. Accelerated life testing arrangement conducted to transformer winding. From this accelerated life test approximate prediction of life of insulating material has analysed. In response to the above tests conducted, satisfactory results achieved.

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