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Modeling, Analysis and Detection of Internal Winding Faults in Power Transformers

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Abstract— Winding inter-turn fault is critical in power transformers since its effect is not easily comprehensible at lower magnitude in the signatures of terminal voltages and currents. This paper presents a new and efficient approach for diagnosing the occurrence of incipient turn to turn short-circuits in the windings of power transformers. The transformer is modeled in steady state and no-load operation. Analysis shows that the phase difference between the input voltage and input current in faulty primary winding is changed in a manner that makes it a good measure to find the fault. A set of laboratory experiments on a custom-built transformer under various levels of faults confirms our theoretical analysis and results.

***Index Terms*—Fault diagnosis, modeling, power transformers.**

I. Introduction

Power transformers are important and costly elements of electric power systems. The continuity of transformers operation is vital in maintaining stability and in improving the reliability of power systems. Any fault in a power transformer affects the operation of connected power system. Therefore the correct and prompt diagnosis of fault in damaged power transformers is of great importance in order to reduce the losses caused by the severe currents and avoid of the instability in power system.

Statistics show that between 70 %-80 % of the number of transformer failures lead eventually to internal winding faults [1]. Winding faults are a result of the degradation of the transformer winding due to aging, high voltages, etc., which tend to cause a breakdown in the dielectric strength of the insulation. This breakdown either causes adjacent windings to short (turn to turn) or a winding to be shorted to ground [2].

The induced EMF in shorted turns is the source of current in shorted turns. The induced current will flow in a direction so that its magnetic field opposes the main flux in the core. Then the input current is increased to keep the main flux constant. The impedance of shorted turns is very low; therefore, a very high current will flow in shorted turns.

According to the IEEE Standard C37.91-2000, in power transformers, for incipient faults or when the number of shorted turns is less than 10 % of total winding turns, there is no significant change in the terminal current to provide protection. Therefore detection and diagnosis of fewer winding inter-turn faults is a difficult task. These faults can lead to a catastrophic failure and hence cause outages if they are not detected in early stages.

Conventional protection for internal winding faults in power transformers is the percentage differential relay. However, this protection does not completely protect the transformer for fewer numbers of shorted turns [3].

Up to now, many methods have been proposed for monitoring and diagnosing of winding inter-turn faults in power transformers.

Dissolved Gas Analysis (DGA) [4]-[10] is currently used for detection of incipient faults. DGA can be used to verify the effects of faults even in the early stages of fault development [4]. The results obtained from the DGA, which are applicable to an in-service transformer, do not clearly determine the cause and origin of faults. Also, it is not applicable for the dry-type, naturally cooled (NC), and air-forced (AF) cooling based transformers [11].

FRA (Frequency Response Analysis) is a well-known and popular method in fault diagnosis in power transformers [12]-[17]. This method got demonstrated in 1978 for detecting winding deformation and inter turn short circuit [12]. Conventional FRA has been relying on a graphical analysis for diagnosis of transformers, which requires trained experts to interpret test results. Hence fault detection by this method especially in first stages is difficult and controversial.

Artificial Neural Network (ANN) [18]-[19] and Wavelet Transforms [20]-[23] can be also applied in transformer diagnostic. However, they are very time-consuming and require many instruments and hardware.

Exciting/differential current Park's Vector Approach has also been proposed for inter-turn fault detection in power transformers [24]-[25]. However, the accuracy of this method is reduced in the presence of imbalances in load and voltage.

A method that is based on the theory of symmetrical components or on the negative-sequence currents is proposed in [26]. However, the transformer needs to be loaded. This method cannot detect the fault at lower value of fault current.

The method introduced in this paper is based on measurement and variations of phase difference between the no-load input voltages and currents in primary windings of power transformers. The transformer is modeled in steady state. In modeling under no-load operation, shorted turns in

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faulty phase behave similar to the secondary of an auto-transformer. A custom-built, 3-kVA, 50-Hz, 380/220-V, 3-phase transformer is designed and constructed in our laboratory to perform a set of experiments. The experimental results show that the proposed method is very efficient and encouraging for the detection of internal faults in the windings of distribution and small power transformers even in early stage.

II. Modeling of Deterioration of Insulation

Due to operating conditions and diverse factors, electrical properties of dielectric material in power transformers may be altered significantly during their life time.

Deterioration and aging of the insulations in a transformer is usually due to the strong electric field that the transformer is encountered with. Incipient internal winding fault in transformers is initiated by deteriorating the insulation between the turns in the windings. Thermal, electrical and mechanical stresses, moisture, and so on are the other factors which generally affect the aging and deterioration of insulation [27].

Generally the electrical behavior of a dielectric material is modeled as a parallel equivalent circuit as is shown in Fig. 1. This model will be used to simulate the incipient internal faults in transformer winding. The resistance R_p represents the power loss in dielectric. The capacitance C_p in this model is given by (1), where C_0 is the equivalent capacitance in the vacuum of the insulation and ζ_r is the relative permittivity or dielectric constant [27].

$$C_p = \zeta_r C_0. \quad (1)$$

The insulation thickness between two layers or two turns in a winding is very thin. So the capacitance in the equivalent circuit has a very small value (about nF) [27]. The capacitive reactance hence will be very large around the power frequency and can be ignored. Therefore, a proper model that simulates the dielectric behavior is an external resistance between the turns. The resistance decreases with more deterioration of the insulation properties. In other words, losses for a perfect insulation is almost zero, but with degradation and aging of insulation, these losses are rising which leads to a reduction in insulation resistance and when the insulation was broken down completely, this resistance will be almost zero.

III. The General Equivalent Circuit of the Transformer in the Presence of Short Circuit in Primary Winding

Under no-load operation, suppose there is an internal fault in one of the primary windings of a power transformer. The faulty winding can be imagined as the primary of an auto-transformer. Short-circuited turns are considered as the secondary winding and the fault impedance acts as an auto-transformer load. Magnetic flux induces an EMF in the faulty turns. As the short circuit occurs across few turns of the

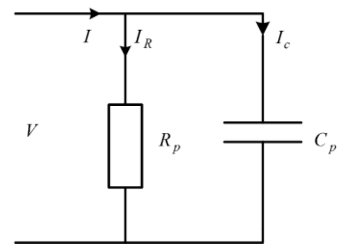

Fig. 1. Parallel Equivalent circuit of a dielectric material.

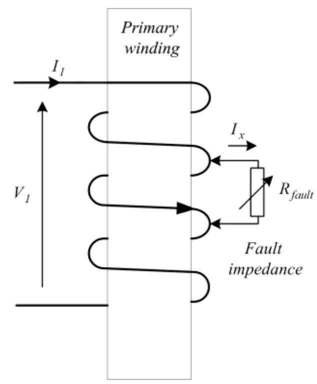

Fig. 2. Equivalent circuit for a fault occurring in the primary winding including the fault resistance R_{fault} [24].

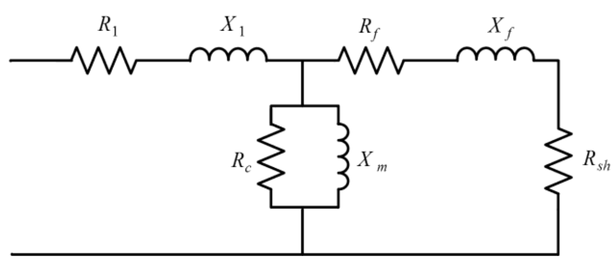

Fig. 3. The equivalent circuit of a no-load transformer referred to the primary side with incipient fault in primary winding.

winding, current flows in the faulty turns. This current generates a magnetic flux that opposes to the initial magnetic flux of the core. Now the input current in the faulty winding increases so that it compensates the effect of current in the shorted turns.

The transformer in the presence of fault in primary winding is shown in Fig. 2, where R_{fault} represents the fault resistance. In this case, the equivalent circuit of the transformer can be considered as shown in Fig. 3.

where

X_1: Leakage reactance of the auto-transformer primary winding;

R_1: Resistance of the auto-transformer primary winding;

X_f: Leakage reactance of faulty winding referred to the primary side;

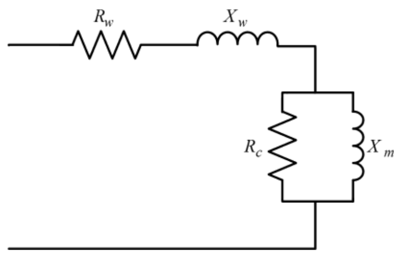

Fig. 4. Equivalent circuit of a healthy transformer in no-load condition.

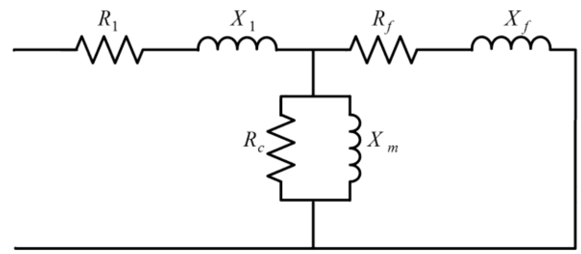

Fig. 5. The equivalent circuit of a no-load transformer referred to the primary side when there is a complete short circuit (without fault impedance) in primary winding.

$$X_f = (a-1)^2 X_2 \,. \tag{2}$$

a: Conversion ratio of auto-transformer (the ratio of the number of turns in the primary to the number of turns that is short circuited);

X_2: Leakage reactance of faulty winding;

R_f: Resistance of faulty winding referred to the primary side;

$$R_f = (R_w \frac{m}{\mathrm{N}_1})(a-1)^2 = R_w \,(\frac{\mathrm{m}}{\mathrm{N}_1})(\frac{\mathrm{N}_1}{\mathrm{m}}-1)^2 \,. \tag{3}$$

R_w: Total resistance of the transformer primary winding;

m: Number of shorted turns;

N_1: Total number of turns in the transformer primary winding;

R_{sh}: Fault resistance referred to the primary side (depicted in Fig. 3);

IV. Theoretical Background

A. Normal condition

Fig. 4 shows the equivalent circuit of one phase of transformer under no-load condition where there are no shorted turns in its windings.

In this case, the input impedance of a healthy transformer neglecting the primary winding impedance [28] can be written as

$$Z_{inh} = X_m \parallel R_c = \frac{R_c X_m{}^2}{R_c{}^2 + X_m{}^2} + j\,\frac{R_c{}^2 X_m}{R_c{}^2 + X_m{}^2} = R_n + j\ \mathrm{X}_n \,. \tag{4}$$

where R_n and X_n are defined as

$$R_n = \frac{R_c X_m{}^2}{R_c{}^2 + X_m{}^2} = X_m \,(\frac{R_c X_m}{R_c{}^2 + X_m{}^2}) \tag{5}$$

$$X_n = \frac{R_c{}^2 X_m}{R_c{}^2 + X_m{}^2} = R_c \,(\frac{R_c X_m}{R_c{}^2 + X_m{}^2}) \tag{6}$$

Therefore the following relationship exists.

$$\frac{X_n}{R_n} = \frac{R_c}{X_m}. \tag{7}$$

The angle of input impedance is calculated as the following:

$$\angle Z_{inh} = \tan^{-1}(\frac{X_n}{R_n}) = \tan^{-1}(\frac{R_c}{X_m}). \tag{8}$$

At no-load condition, the transformer acts as a single winding with high self-inductance so that for most of distribution and power transformers the no-load power factor averages about 0.15 lagging [29]. This means that the angle of input impedance at no-load condition is around 80 degrees and the value of core resistance (R_c) is approximately 6-7 times the value of magnetizing reactance (X_m) (so X_n = 6-7 times R_n). Therefore, the transformer input current lags approximately the input voltage by an angle of 80 degrees. For some extra high voltage transformers, this is not true because the no-load power factor may be around 0.85. Therefore, the analysis and the proposed method of fault diagnosis in this paper are valid for those transformers with lower values of no-load power factors.

B. Faulty condition

Suppose there is a complete internal short circuit across a few turns in the primary winding. As regards less number of turns is challenging in the detection and diagnosis of faults, our goal is focused on these cases. Here, analysis is valid for the case where the magnetic fluxes of the two healthy phases are not altered due to the fault current in shorted turns. At high number of shorted turns, the magnetic flux distribution is fundamentally altered in a way that the magnetic fluxes of the other two phases are changed and so their no-load currents.

According to the equivalent circuit shown in Fig. 5, the input impedance can be evaluated.

Actual value of resistance and leakage inductance of shorted turns are very low especially for low number of shorted turns i.e. one, two or five turns. However, the ratio of the number of turns in the primary winding to the number of turns that is short circuited is actually high. Therefore the referred values of these quantities to the primary side are so that their combination with $Z_n=R_n+jX_n$ determine the major part of input impedance of the faulty phase winding. On the other hand, the impedance of primary winding ($Z_1= R_1+ jX_1$) is negligible to both Z_n and $Z_f=R_f+jX_f$ and their series combination. Therefore, the input impedance Z_{inf} can be written as

$$\begin{aligned} Z_{\mathrm{inf}} &= R_{\mathrm{inf}} + j\ \mathrm{X}_{\mathrm{inf}} = ((\mathrm{R}_n + jX_n) \parallel (\mathrm{R}_f + jX_f)) = \\ &(\frac{R_n{}^2 R_f + R_f{}^2 R_n + X_f{}^2 R_n + X_n{}^2 R_f}{(\mathrm{R}_{nf})^2 + (\mathrm{X}_{nf})^2}) + \\ &j\,(\frac{R_n{}^2 X_f + R_f{}^2 X_n + X_n{}^2 X_f + X_f{}^2 X_n}{(\mathrm{R}_{nf})^2 + (\mathrm{X}_{nf})^2}). \end{aligned} \tag{9}$$

where $R_{nf} = \mathrm{R}_n + \mathrm{R}_f$ and $\mathrm{X}_{nf} = \mathrm{X}_n + X_f$.

The angle of input impedance is calculated as

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$$\angle Z_{\inf} = \tan^{-1}(\frac{X_{\inf}}{R_{\inf}}) = \tan^{-1}\frac{R_n^{\,2}X_f + R_f^{\,2}X_n + X_n^{\,2}X_f + X_f^{\,2}X_n}{R_n^{\,2}R_f + R_f^{\,2}R_n + X_f^{\,2}R_n + X_n^{\,2}R_f}. \tag{10}$$

It is seen that under faulty condition, the above angle is dependent on R_f and X_f. If this dependence obeys a systematic rule, it is possible to find a method to detect the inter-turn fault in a transformer. Our study shows that it can be used efficiently for our purpose.

An accurate inspection of (10) shows that the angle of input impedance varies considerably as the number of shorted turns varies. Suppose that $\angle Z_{\inf}$ is smaller than $\angle Z_{\mathrm{inh}}$. To satisfy this condition, using (8) and (10) the following inequality has to be checked:

$$\tan^{-1}\frac{R_n^{\,2}X_f + R_f^{\,2}X_n + X_n^{\,2}X_f + X_f^{\,2}X_n}{R_n^{\,2}R_f + R_f^{\,2}R_n + X_f^{\,2}R_n + X_n^{\,2}R_f} < \tan^{-1}(\frac{X_n}{R_n} = \frac{R_c}{X_m}). \tag{11}$$

Or

$$\left(\frac{R_n^{\,2}\frac{X_f}{X_n} + R_f^{\,2} + X_n X_f + X_f^{\,2}}{R_n R_f + R_f^{\,2} + X_f^{\,2} + X_n^{\,2}\frac{R_f}{R_n}}\right) < 1. \tag{12}$$

$$R_n^{\,2}\frac{X_f}{X_n} + X_n X_f < R_n R_f + X_n^{\,2}\frac{R_f}{\mathrm{R}_n}. \tag{13}$$

$$X_f\,(\frac{R_n^{\,2}}{X_n} + X_n) < R_f\,(R_n + \frac{X_n^{\,2}}{\mathrm{R}_n}). \tag{14}$$

This leads to

$$\frac{X_f}{X_n} < \frac{R_f}{R_n}. \tag{15}$$

Using (7)

$$\frac{X_f}{R_f} < (\frac{X_n}{R_n} = \frac{R_c}{X_m}). \tag{16}$$

To satisfy (16), $\angle Z_{\inf}$ must be smaller than $\angle Z_{\mathrm{inh}}$.

For incipient faults where the short circuit between the turns is starting to appear, according to Fig. 3, short circuit occurs through the resistance R_{sh}. Considering R_{sh}, the angle of input impedance is calculated as

$$\angle Z_{\inf} = \tan^{-1}\frac{X_n(R_n^{\,2}\frac{X_f}{X_n} + X_n X_f + X_f^{\,2} + \mathrm{R}_{sh-f}^{\,2})}{R_n(X_f^{\,2} + X_n^{\,2}\frac{R_{sh-f}}{\mathrm{R}_n} + R_n\,\mathrm{R}_{sh-f} + R_{sh-f}^{\,2})}. \tag{17}$$

where $R_{sh-f} = R_{sh} + R_f$.

After some simplification, if the following inequality is satisfied it is seen that the angle of input impedance in faulty condition is decreased compared to the normal condition. Any increase of number of shorted turns leads to more decrease in the angle of input impedance.

$$\frac{X_f}{R_f + R_{sh}} < \frac{R_c}{X_m}. \tag{18}$$

Now we need to verify this condition. In the following we calculate the leakage inductance of faulty winding.

C. Calculation of leakage inductance of shorted turns

The leakage inductance of faulty winding is calculated using finite element method (FEM). A two dimensional magneto-static solution is performed and a linear magnetic core is considered. Poisson's equation for magneto-static field is obtained as the following:

$$\nabla^2 \mathbf{A} = -\boldsymbol{\mu}\mathbf{J_e}. \tag{19}$$

Solution region is divided into triangular elements. There are N elements and n_e nodes. (**A**) is a matrix consists of the values of magnetic vector potential, $\mathbf{J}_e$ is a matrix consists of source terms, and $\boldsymbol{\mu}$ is a matrix consists of magnetic permeability at each node in the solution region. Elements of $\boldsymbol{\mu}$ are $\mu_o\mu_r$ for iron part and μ_o for non-iron part.

To calculate the leakage inductance of shorted turns, magnetic vector potential **(A)** is found only due to the current in shorted turns. Therefore, specified elements of $\mathbf{J}_e$ in (19) are set to the circulating current density in shorted turns as the source of magnetic field in the transformer. Using (**A**), magnetic energy in transformer core W_m and magnetic energy in spaces surrounding the shorted turns W_l are calculated. The main inductance of shorted turns L_m is related to W_m whereas the leakage inductance L_l is related to W_l. Total magnetic energy is sum of W_m and W_l.

Total magnetic energy per unit length is calculated as the following:

$$F(\mathbf{A}) = \sum_{e=1}^{N} F(\mathbf{A_e}) = \frac{1}{2\mu}[\mathrm{A}]^t[\mathrm{C}][\mathrm{A}] = \frac{1}{2\mu_0\mu_r}[\mathrm{A}_c]^t[\mathrm{C}_c][\mathrm{A}_c] + \frac{1}{2\mu_0}[\mathrm{A}_a]^t[\mathrm{C}_a][\mathrm{A}_a]. \tag{20}$$

where

$\mathbf{A_e}$: Magnetic potential distribution over each element;

$F(\mathbf{A_e})$: Total energy per unit length within element e;

$\mathbf{C}$, $\mathbf{C_c}$ and $\mathbf{C_a}$: Global coefficient matrices for total solution region, for the core and for the non-core parts, respectively;

A_c: Magnetic vector potential in the core part;

A_a: Magnetic vector potential in the none-core part;

At the second line of equation (20), the first term corresponds to magnetic energy stored in transformer core W_m and the second term corresponds to magnetic energy stored in non-core part surrounding the shorted turns W_l.

Now each part of the inductance could be found through the following equation.

$$W = W_m + W_l = \frac{1}{2}L_m I^2 + \frac{1}{2}L_l I^2. \tag{21}$$

where I is the current in shorted turns.

The leakage inductance of shorted turns L_l is related to W_l.

$$\mathrm{L}_l = \frac{D}{\mathrm{I}^2\,\mu_0}[\mathrm{A}_a]^t[\mathrm{C}_a][\mathrm{A}_a]. \tag{22}$$

D is the depth of transformer core.

In the following, the main and leakage inductance for

TABLE I
GENERAL SPECIFICATIONS OF TWO TYPICAL TRANSFORMERS.

	Transformer 1	Transformer 2
Power	6.5 MVA	250 kVA
Frequency	50 Hz	50 Hz
Voltage	15/6.9 kV	6600/400-440 V
Transformer type	Core type	Core type
Connection method	$Y\ \Delta$	ΔY
Turn ratio	350/93	858/30
Winding type	Layer/ Continuous disc	Layer/ cross over

TABLE II
THE MAIN AND LEAKAGE INDUCTANCE OF SHORTED TURNS IN SAMPLE TRANSFORMERS CALCULATED BY PROPOSED METHOD.

No. of shorted turns	Transformer 1 6.5-MVA	Transformer 2 250-kVA
1 turn	$L_m = 136\mu H$	$L_m = 79\mu H$
	$L_l = 0.65\mu H$	$L_l = 2.62\mu H$
2 turn	$L_m = 544\mu H$	$L_m = 316\mu H$
	$L_l = 3.2\mu H$	$L_l = 15.7\mu H$
5 turn	$L_m = 4mH$	$L_m = 2mH$
	$L_l = 40.5\mu H$	$L_l = 0.13mH$

TABLE III
CALCULATED RESISTANCE AND LEAKAGE REACTANCE OF SHORTED TURNS IN HV WINDING OF SAMPLE TRANSFORMS.

	No. of shorted turns	Resistance (in ohm) and Leakage reactance (in ohm) of shorted turns referred to the source side	$\frac{X_f}{R_f}$
6.5-MVA Transformer	1 turn	$X_f = 24.78\ \ R_f = 84$	0.29
	2 turn	$X_f = 30.8\ \ R_f = 42$	0.73
	5 turn	$X_f = 60.5\ \ R_f = 16.8$	3.6
250-kVA Transformer	1 turn	$X_f = 673\ \ R_f = 8.9*10^4$	0.007
	2 turn	$X_f = 920\ \ R_f = 4.46*10^4$	0.021
	5 turn	$X_f = 1194\ \ R_f = 1.78*10^4$	0.067

TABLE IV
SINGLE PHASE EQUIVALENT CIRCUIT PARAMETERS OF THE TESTED TRANSFORMER, OBTAINED FROM SHORT CIRCUIT AND OPEN CIRCUIT TESTS.

Parameters values of the tested transformer	
Primary winding resistance	1 ohm
Secondary winding resistance	0.2 ohm
Primary winding leakage reactance	0.64 ohm
Secondary winding leakage reactance	0.197 ohm
Magnetizing reactance	465 ohm
Core loss resistance	1290 ohm

different number of shorted turns for two typical transformers are calculated. General specifications of these transformers are given in Table I and the calculated inductances are given in Table II.

Also the resistance of shorted turns is calculated and the relation given in (16) is verified. Table III shows the results. Considering the no-load power factor of each transformer, the ratio R_c/X_m of each transformer is calculated. If the relationship given in (16) is satisfied, it is possible to detect the existence of shorted turns in transformer. For example suppose the no-load power factor of 250-kVA transformer is 0.15 then the ratio of R_c/X_m is equal to 6.59. Calculated values of X_f/R_f given in table III shows that the inequality obtained in (16) is satisfied for 1, 2, and 5 numbers of shorted turns. Therefore, the proposed method can be applied completely to detect the existence of shorted turns even 1 turn (i.e. (1/858)*100=0.11 % number of primary turns).

Calculated values of X_f/R_f for 6.5-MVA transformer given in table III show that if the no-load power factor of this transformer is around 0.24 (i.e. R_c/X_m=4), the inequality given in (16) is satisfied for 1, 2 and 5 numbers of shorted turns. Hence for 6.5-MVA transformer, the proposed method can detect even 1 number of shorted turns (i.e. (1/350)*100=0.29 % number of primary turns).

V. Experimental setup

A. *Laboratory Transformer*

A three-phase, YY, core type, 3-kVA, 380-V/220-V transformer was designed and constructed for the experiments. The primary winding has 270 turns and the secondary has 150 turns. Short circuit and open circuit tests are performed to obtain the equivalent circuit parameters of the transformer. The results are shown in Table IV.

To establish the short circuit between the primary turns, additional wires are soldered to the selected turns, 250th, 255th, 257th, and 258th turn in primary winding. Wires are extracted out to create the short circuit faults in primary winding. It should be noticed that the resistance of these wires, acts as the fault resistance R_{fault}. Fig. 6 shows the general view of our laboratory transformer.

Fig.6. Picture of the test transformer.

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TABLE V
CALCULATED PHASE DIFFERENCE BETWEEN THE FUNDAMENTAL COMPONENTS OF THE INPUT VOLTAGE AND THE INPUT CURRENT IN R- PHASE UNDER DIFFERENT CONDITIONS (Y-Y CONNECTION).

Condition	Resistance of external wires (ohm)	Angle of input impedance (degree)
Normal	-	70
Short circuit between 257th and 258th turns in R-phase	0.01	48
Short circuit between 255th and 257th turns in R-phase	0.005	21
Short circuit between 250th and 255th turns in R-phase	0.008	8

B. Calculation of angle of input impedance in constructed transformer

Angles of input impedance are calculated in the normal and in the faulty conditions, separately using the equivalent circuit obtained for the laboratory transformer.

In the experiments, short circuit is established through the external wires. The resistance of external wires has been considered in the calculations, too.

Table V shows the resistance of external wires and the phase difference between the fundamental components of R-phase voltage and R-phase current under normal and faulty conditions.

The results in Table V show that as the number of shorted turns increases, the angle of input impedance or the phase difference between the fundamental components of phase voltage and phase current in faulty phase decreases considerably.

VI. Evaluation of experimental results

The experimental investigation was carried out to verify the presented model and theoretical bases. Steady state input voltages and currents were analyzed. High voltage windings were connected to the 380-V line to line voltage and experiments are performed under no load condition. Waveforms of the input voltage and the input current in R-phase (faulty phase) are shown in Fig. 7. Per-unit values of voltages and currents are plotted. It is seen that as the fault occurs and expands in primary winding, phase difference of the input voltage and the input current decreases significantly in faulty winding. Experimental results show that the phase difference between the input voltage and the input current in the other two healthy windings has no significant variation while the number of shorted turns is low. Table VI gives the phase difference between the fundamental components of R-phase voltage and R-phase current under normal and faulty conditions. These results have very close agreement to the calculated results shown in Table V.

Small differences between the calculated and experimental results are due to some unbalances in applied line voltages, and unavoidable errors in the calculation of single phase equivalent circuit of the laboratory transformer.

Alternatively, instead of measurement of phase difference between the fundamental components, we can measure the phase difference between the overall input voltage and the

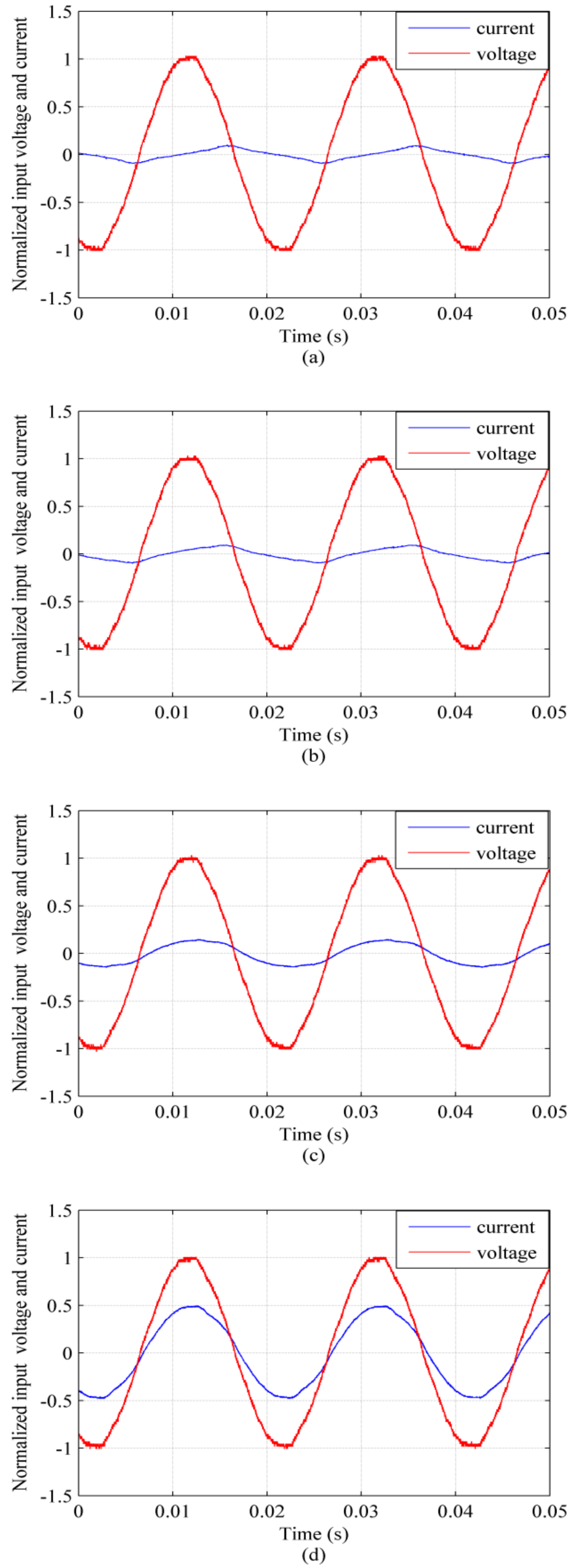

Fig. 7. Waveforms of input voltage and current of R-phase that was measured during experiments with line voltage 380-V for
(a) Normal case (The RMS value of current is 0.45-A).
(b) 1 turn short circuited (The RMS value of current is 0.5-A).
(c) 2 turns short circuited (The RMS value of current is 0.8-A).
(d) 5 turns short circuited (The RMS value of current is 2.5-A).

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TABLE VI
PHASE DIFFERENCE BETWEEN THE FUNDAMENTAL COMPONENTS OF THE INPUT VOLTAGE AND THE INPUT CURRENT IN R-PHASE UNDER DIFFERENT CONDITIONS, MEASURED IN EXPERIMENTS (Y-Y CONNECTION).

Condition	Resistance of external wires (ohm)	Angle of input impedance (degree)
Normal	-	79
Short circuit between 257th and 258th turns in R-phase	0.01	55
Short circuit between 255th and 257th turns in R-phase	0.005	18
Short circuit between 250th and 255th turns in R-phase	0.008	6

TABLE VII
THE PHASE DIFFERENCE BETWEEN THE OVERALL INPUT VOLTAGE AND OVERALL INPUT CURRENT IN R-PHASE UNDER DIFFERENT CONDITIONS MEASURED IN EXPERIMENTS (Y-Y CONNECTION).

Condition	Resistance of external wires (ohm)	Angle of input impedance (degree)
Normal	-	85
Short circuit between turns 257-258 in R-phase	0.01	49
Short circuit between turns 255-257 in R-phase	0.005	18
Short circuit between turns 250-255 in R- phase	0.008	8

TABLE VIII
THE PHASE DIFFERENCE BETWEEN THE OVERALL INPUT PHASE VOLTAGE AND OVERALL INPUT PHASE CURRENT UNDER DIFFERENT CONDITIONS MEASURED IN EXPERIMENTS (D-Y CONNECTION).

Condition	Phase difference in (degree)	
	R-phase	S-phase
Normal	82	73
Short circuit between turns 257-258 in R-phase	70	57
Short circuit between turns 255-257 in R-phase	57	13
Short circuit between turns 250-255 in R- phase	43	14 lead

overall input current in faulty phase. Our investigation shows that the error due to this approximation is negligible. However, it is much easier to measure the phase difference using the overall signals and not their fundamentals. Summary of the results using the overall signals are given in Table VII.

To confirm and to show the effectiveness of the analytical approach and the proposed method for fault detection for various winding connections, the primary side of laboratory transformer is changed to delta connection. Faulty winding is connected between phase R and phase S of the three phase power supply. We name the faulty winding as RS winding. Table VIII gives the phase difference between the overall input phase voltage and the overall input phase current in R and S phases, respectively. It is seen that as the fault occurs and expands in RS winding, phase difference between the input phase voltage and the input phase current in phase R and phase S decrease significantly. Experimental results show that the phase difference between the input phase voltage and the input phase current in phase T has no significant variation. Faulty winding has no direct connection to Phase T. So the experimental results show that the method is applicable to D-Y connection too.

VII. CONCLUSION

Under steady state, no-load operation power factor of a power transformer is approximately very low. Hence its behavior is similar to a winding with a high inductance. For a star-star 3-phase power transformer at no-load operation, the secondary windings are open circuited. If there is any turn to turn short circuit (even through a fault resistance) in one of the primary windings, this winding and short circuited turns can be considered as the primary and secondary windings of an auto transformer, respectively. Magnetic flux induces an EMF in the faulty turns. As the short circuit occurs across these turns, current flows in the faulty turns. This current generates a magnetic flux that opposes to the initial magnetic flux of the core. Now the input current to the faulty winding increases to compensate the effect of current in the short circuited turns. Theoretical and experimental results confirm that for internal faults with low number of turns (e.g. 1 turn, 2 turns), the equivalent impedance of faulty turns is mostly resistive. In other words, compensating component in the current through the faulty winding is approximately in phase with its applied voltage. Under this condition, for Y-Y connection, the phase difference between the input voltage and the input current of the phase connected to faulty winding decreases considerably with respect to the normal no-load operation. For few shorted turns, the phase differences in the other healthy windings do not alter significantly. Successful experimental results for D-Y connection of our laboratory transformer show that the proposed method is applicable to various winding connections Y or D. Therefore, the analysis is valid and the method presented to detect the internal fault in initial stage is applicable. The method proposed in this work is suitable for no-load operation of transformer; and the validity of the method with on-load and OLTC operation is the next step to pursue.

REFERENCES

[1] Mirrasoul J. Mousaviand Karen L. Butler-Purry, “Transformer internal incipient fault simulations,” in *Proc. 2003 North American Power Symposium, Rolla, MO*, 2003, pp. 195-203.
[2] Karen L. Butler and Adedayo Kuforiji, “Experimental results from short-circuit faults on a distribution transformer,” *in Proc. IEEE Transmission and Distribution Conf.*, vol.1, Oct. 2001, pp. 299-306.
[3] IEEE Guide for Protective Relay Applications to Power Transformers, IEEE Std C37.91-2000.
[4] N. Yadaiah and Nagireddy Ravi, “Fault detection techniques for power transformers,” *in Proc. Industrial & Commercial Power Systems Technical Conf.*, vol. 6, May 2007, pp. 1-9.
[5] C. E. Lin, J. M. Ling, and C. L. Huang, “An expert system for transformer fault diagnosis using dissolved gas analysis,” *IEEE Trans. Power Delivery*, vol. 8, no. 1, pp. 231 – 238, January 1993.
[6] A. Varl and M. Končan-Gradnik, “Early detected transformers incipient faults by means of physical-chemical diagnostics,” *in Proc. IEEE Int. Conf. on Dielectric Liquids*, 2005, pp. 253-256.
[7] Michael Webb, “Anticipating failures by dissolved-gas monitoring,” *IEEE Power Engineering Journal*, vol.1, pp. 295-298, Sept. 1987.

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[8] Ena Narang, Er. Shivani Sehgal, Er. Dimpy Singh, “Fault detection techniques for transformer maintenance using dissolved gas analysis,” *International Journal of Engineering Research & Technology (IJERT)*, vol. 1, no.6, August 2012.

[9] Stan Lindgren, “Power transformer asset management on-line DGA - The New Ballgame,” presented at EPRI Substation Equipment Diagnostics Conf. XI, New Orleans, Louisiana, February 23-26, 2003.

[10] Sherif S. M. Ghoneim and Sayed A. Ward, “Dissolved gas analysis as a diagnostic tools for early detection of transformer faults,” *Advances in Electrical Engineering Systems (AEES)*, vol. 1, no. 3, pp. 152-156, 2012.

[11] R. S. Bhide, M. S. S. Srinivas, A. Banerjee, and R. Somakumar, “Analysis of winding inter-turn fault in transformer: A Review and Transformer Models,” *in Proc. ICSET*, 2010, pp. 1-7;

[12] E.P. Dick and C.C. Erven, “Transformer diagnostic testing by frequency response analysis,” *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-97, no. 6, pp. 2144-2153, Nov. 1978.

[13] Syed Mofiml Islam, “Detection of shorted turns and winding movements in large power transformers using frequency response analysis,” *in Proc. Power Engineering Society Winter Meeting*, vol.3, 2000, pp. 2233–2238.

[14] Jong-Wook Kim, ByungKoo Park, Seung Cheol Jeong, Sang Woo Kim, and PooGyeon Park, “Fault diagnosis of a power transformer using an improved frequency-response analysis,” *IEEE Trans. Power Delivery*, vol. 20, no. 1, pp. 169 –178, January 2005.

[15] J. Chong and A. Abu-Siada, “A novel algorithm to detect internal transformer faults,” *in Proc. Power and Energy Society General Meeting*, 2011, pp. 1-5.

[16] Suwarno and F. Donald, “Frequency response analysis (FRA) for diagnosis of power transformers,” *in Proc. Int. conf. on (ECTI-CON)*, May 2010, pp. 112-116.

[17] M.R. Barzegaran, M. Mirzaie, and A. Shayegani Akmal, “Frequency response analysis in power transformer for detection of winding short-circuit using quasi-static finite element and circuit-based method,” *World Applied Sciences Journal 7 (8*), pp. 1006-1015, 2009.

[18] Atthapol Ngaopitakkul and Anantawat Kunakorn, “Internal fault classification in transformer windings using combination of discrete wavelet transforms and back-propagation neural networks,” *International Journal of Control, Automation, and Systems*, vol. 4, no. 3, pp. 365-371, June 2006.

[19] H. Wang, K. L. Butler, “Modeling transformer internal short circuit faults using neural network techniques,” *in Proc. Annual Report Conf. on Electrical Insulation and Dielectric Phenomena*,2005, pp. 601-604.

[20] Karen L. Butler-Purry, and Mustafa Bagriyanik “Characterization of transients in transformers using discrete wavelet transforms,” *IEEE Trans. Power Systems*, vol. 18, no. 2, pp. 648 – 656, May 2003.

[21] M. R. Rao and B. P. Singh, “Detection and localization of interturn fault in the HV winding of a power transformer using wavelets,” *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 8, no. 4, pp.652-657, August 2001.

[22] O. Ozgonenel, D.W.P. Thomas, and C. Christopoulos, “Modeling and identifying of transformer faults,” *in Proc. Power Tech, IEEE Russia*, 2005, pp. 1-7.

[23] N. Y. Abed and O. A. Mohammed, “Modeling and characterization of transformers internal faults using finite element and discrete wavelet transforms,” *IEEE Trans. Magnetics*, vol. 43, no. 4, pp. 1425-1428, April 2007.

[24] Luís M. R. Oliveira, and A. J. Marques Cardoso, “Detection of transformer intermittent winding faults by the on-Load exciting current Park's Vector Approach,” *in Proc. of the 20th Int. Congress on Condition Monitoring and Diagnostic Engineering Management*, June 2007, pp. 263-272,

[25] Luís M. R. Oliveira, A. J. Marques Cardoso, and Sérgio M. A. Cruz, “Transformers on-load exciting current Park's Vector Approach as a tool for winding faults diagnostics,” presented atthe 15th Int. Conf. on Electrical Machines (ICEM), Brugge, Belgium, August 25-28, 2002.

[26] Zoran Gajić, Ivo Brnčić, Birger Hillström, Fahrudin Mekić and Igor Ivanković, "Sensitive turn-to-turn fault protection for Power transformers,” *in Proc. of the 60th Georgia Tech Protective Relaying Conf. : Georgia Tech Global Learning & Conference*, 2006.

[27] Hang Wang, and Karen L. Butler, “Modeling transformers with internal incipient faults, *IEEE Trans. Power Delivery*, vol. 17, no. 2, pp. 500-509, April 2002.

[28] *Electric power transformer engineering*, 3rd ed CRC Press Co., USA, 2007.

[29] Martin J. Heathcote, “Transformer theory,” *in The J&P Transformer Book*, 12th ed., Great Britain, 1998, pp. 5.

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