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Transformer's internal short circuit fault detection by using transmission line model

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ABSTRACT
In this study, a new approach is proposed for modeling power transformers internal faults by using transmission line model (TLM) and also presented a method to forecasting these kinds of faults by monitoring the effect of partial discharges on transformer primary side current. These monitoring actions boost the reliability of power system. Simulating and detecting loop to loop and loop to ground faults between the desired Transformer's coil wires in early stages is advantage of this method. Finally, Transformers TLM is implemented with Matlab for observing this method. Simulation results verified application of proposed modeling technique for studying and detecting power transformers different short-circuit faults conditions.

Introduction

According to the cost and the importance of high power Transformers, it is very useful that numbers and periods of unwanted disruptions minimized. Protection of high power Transformers is super challenging problem in relaying Power systems. Development and validation of algorithms for Transformers protection are initial need of power Transformer model. This model should simulate all situations that may choose for study case. Specifically, the model must be able to simulate the internal and external faults. Main Problem that may happen to computer monitoring systems is that Transformers faults may not be discovered at its starting point. Experience has shown that most internal power Transformers faults start from small drain from there tanks, If these currents leakage continue, they will lead to future damage, Dielectric breakdown is accelerated and leading to a more serious and persistent errors. Nowadays, transformers early faults discovered by Analyzing of collected gas in the tank which is the result of combustion process. These faults can be detected by developing a technique that discovers Transformers current characteristic in which early fault happened. These current changes which caused by the early error will be very difficult to detect, because this current is too small Compared to the load current of Transformers. An annually registered surveys on Modern Transformers failure shows that 70 to 80 percent of failure caused by winding's Loops fault. In 1960, W.Lech & L. Tyminski found that by applying impulse voltage with low amplitude to transformer input and Sampling shock wave across it, mechanical deformation of coil detected. In 1966, Lech and Tyminski studies on detection of coil deformation based on input impulse voltage was published in England. In 1976, Method for analyzing Transformers response to impulse voltage in the frequency domain was proposed by AG Richenbacher. In 1976, an article "The frequency response, a method for testing and troubleshooting," by CC Erven and E.P. Dick was published. In [10] also used a similar approach based on the frequency modeling. In the same year this approach was employed at Ontario Hydro Company, conducted Tests by European companies between 1988 and 1990 shows that it was successful. Until now numerous papers in support and development of this approach were published [1]-[5]. Recently, in test and control stage of power transformers, producers consider frequency response measurements of Transformers which known as a transformer fingerprint. Before and after transport, after extreme short circuit in the network, Transformers are being checked by frequency response method for its functioning state. It is verified that identical Transformers, in terms of design (sister unit), have similar frequency response. this approach have many disadvantages, There was no comparison between results of transformer and reliable reference, Frequency response measurement technique of transformer should be similar with reference one and inability of this approach for bringing analytical method for analyzing difference of measured results with reference results. in [4] transfer function of the coil used for locating partial leakage. For this purpose it is necessary To have transfer functions of all internal points toward both ending point of coil should be provided. But these functions can not be calculated directly, it should be calculated from model. Since the partial discharging pulses are greatly sharp, their frequency spectrum includes a wide range. In [6] Transformers winding modeling based on previous detailed model has been done. In this case very fast transient caused by switching or lightning have been studied. In [7] Flux distribution in the core and around and modeling winding Transformers calculated by using finite element method. Study in reference [8] shown that if used model support Wide range of frequency spectrum of partial discharging current, good results obtained for location of partial discharging. This paper used a new approach for detecting transformers internal faults. Development of proposed model (TLM) is presented In Section 2, Section 3 illustrated data of sample Transformers Used in the simulation and in Section 4 obtained simulation results shown.

Proposed model development

TLM method for the first time was developed in early 1970 to model two-dimensional problem. Then it was developed for three-dimensional problems and simulation of wide circuits. TLM models can be used to develop a discrete circuit models directly from a system without specifying any Integral and

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differential Relations [11]. TLM model is inherently discrete algorithm and it is quite suitable for use in computers [13]. TML Techniques base is linear model of reactive components, which are called stubs, such as transmission line. Stub model represents an inductive element to confirm induction behavior which will lead to a short circuit, so storage in a magnetic field should be maximized. TLM model for a capacitor is a stub with an open circuit (the ends of an open circuit). Voltage stored in the electric field is important and so is the basic behavior of capacitor [12] - [14]. For modeling and analysis of the internal faults, inductance calculation is a basic part. The existed analytical methods for Short circuit fault of power Transformers have many weaknesses, such as coil linear inductance definition [15], waste lot of time [16] , [17] (i.e. methods based on finite element). If an internal error occurs in winding, winding is divided into three subdivisions shown in Figure 6. Each subsection is represented by an equivalent inductance and subsequently their TLM models. Short circuit stub resistance can be ignored because the normal stub resistance is much larger. In terms of internal error, the system matrix is updated according to the system new condition. According to described procedures in the above analysis, the proposed model for the internal short circuit fault should satisfy the following two requirements:

1) The primary and secondary side currents are obtained by coupled circuit equations (KVL) and TML models at each time step.

2) Inductance of a coil is calculated directly from BH curve at each time step.

These two issues are principals of problem and will be discussed in the next section.

Inductor modeling

TLM model of a linear inductor is shown in Figure 1. Each differential part can be replaced by a discrete conversion equation 1. In most applications, it is necessary to consider the nonlinear behavior of capacitor and inductor. Non-linear capacitor and inductor can be modeled as nonlinear stub. relations between voltage and current is not clear due to leakage flux, eddy currents and etc, this problem can be solved by non-linear analysis. Figure 2 shown modeling of a non-linear inductor with its TLM Thevenin equivalent circuit. Voltage drop on the dependent current inductor is shown in equation 2 [14].

$$Z_L i + 2V_L^i \tag{1}$$

Where

$$Z_L = \frac{2L}{\Delta t}$$

Δt = Time step

V_L^i = Emitted pulses

$$\begin{aligned} V_L &= \frac{d\lambda}{dt} \\ &= L(i)\frac{di}{dt} \\ &= L(i)\left[1\frac{di}{dt}\right] \\ &= L(i)V_{Lu} \end{aligned} \tag{2}$$

Term inside the brackets in equation 2 represents the voltage drop across the 1H inductor.

Figure 1: (a) inductor; **(b)** inductor stub Model; **(c)** inductor TLM equivalent circuit

Stub model of inductor is presented by normal method shown by equation (3). Therefore, voltage of inductor L_i is calculated by equation (4).

$$V_{Lu} = L(i)\left[\ Z_{Lu} + 2V^i{}_{Lu}\right] \tag{3}$$

Where

$$Z_{Lu} = \frac{2}{\Delta t}$$

$$V_L = L(i)\left[Z_{Lu} i + 2V_{Lu}^i\right] \tag{4}$$

Equation (4) and equivalent circuit is used to find the inductor current. At each time step, the value of L_i is updated then V_{Lu} is calculated. The new voltage is calculated by using equation (5)

$${}_{k+1}V_{Lu}^{i} = {}_{k}V_{Lu}^{i} - {}_{k}V_{Lu} \tag{5}$$

If skin effect was ignored due to coil's loop DC resistance, this modeling approach (equations 1 to 3) will be modified. Magnetic coupling between components is described by using TLM technique. A typical configuration of a non-linear inductor, which described above, is shown in Figure 1(a). Mutual coupling is modeled using a controlled voltage source, Resulted Thevenin equivalent circuit is shown in Figure 1(c). Controlled sources equations are shown in equations (6) and (7).

$$V_{m12} = M_{12}(i_1)\left[i_2 Z_{Lmu} + 2V_{Lmu}^i\right] \tag{6}$$

$$V_{m21} = M_{21}(i_2)\left[i_1 Z_{Lmu} + 2V_{Lmu}^i\right] \tag{7}$$

Solving process continue by applying KVL rule for two circuits of Figure 3b. These relations derived from relations (4), (6) and (7)

$$\begin{aligned} V_s = {} & i_1\left(R_s + R_1\right) + L_1\left(i_1\right)\left[Z_{L_1u} i_1 + 2V_{L_1u}^i\right] \\ & + M_{12}\left(i_2\right)\left[i_2 Z_{Lmu} + 2V_{Lmu}^i\right] \end{aligned} \tag{8}$$

$$\begin{aligned} 0 = {} & i_2\left(R_2 + R_L\right) + L_2\left(i_2\right)\left[Z_{L_2u} i_2 + 2V_{L_2u}^i\right] \\ & + M_{21}(1)\left[i_1 Z_{Lmu} + 2V_{Lmu}^i\right] \end{aligned} \tag{9}$$

R_s and R_1 are source and primary side resistances, respectively. R_2 and R_L are secondary side and load resistances, M_{12} and M_{21} are mutual inductance of L_1 and L_2 (primary and secondary side inductances). At the beginning of the simulation, all initial values are set to zero, This was assumed because there is no residual flux in Transformer's core. After solving equations, i_1 and i_2 were obtained, voltages of TLM model are calculated by equations (7)-(10).

Figure 2: (a) a non-linear inductor; **(b)** non-linear inductor TLM model

Figure 3: A sample Transformers with nonlinear inductor

$$i_2 = ((M_{12}V_s - 2M_{12}M_{21}V^i_{Lmu} - 2L_1M_{12}V^i_{L_1u})Z_{Lmu} + (2L_1M_{21}V^i_{Lmu} + 2L_1L_2V^i_{L_2})Z_{L_{1u}} + (2M_{21}R_s + M_{21}R_1)V^i_{Lmu} + (2L_2R_sV^i_{L_2u} + 2L_2R_1V^i_{L_2u})) / (M_{12}M_{21}Z^2_{Lmu} + L_1Z_{L_1u}(-L_2Z_{L_2u} - R_L - R_2) + R_s(L_2Z_{L_2u} - R_L - R_2) + R_1(L_2Z_{L_2u} - R_L - R_2)) \quad (10)$$

New distributed voltages are calculated by using Equation 6 and the following relations:

$${}_{k+1}V^i_{L_1} = {}_kV^i_{L_1} - {}_kV_{L_1} \quad (11)$$

$${}_{k+1}V^i_{L_2} = {}_kV^i_{L_2} - {}_kV_{L_2} \quad (12)$$

$${}_{k+1}V^i_{M_{12}} = {}_kV^i_{M_{12}} - {}_kV_{M_{12}} \quad (13)$$

$${}_{k+1}V^i_{M_{21}} = {}_kV^i_{M_{21}} - {}_kV_{M_{21}} \quad (14)$$

Where k is simulation time step

These values are placed in equations (9) and (10) to calculate next time steps current. For having more complete Transformers model, leakage inductance can be added. TLM model of nonlinear Transformers with considering its both side leakage inductances is shown In Figure 4. $V_{L_{e1}}$ and $V_{L_{e2}}$ are leakage inductors voltages of transformer's primary side and secondary side, respectively. If both primary and secondary side leakage inductances are considered, the following relations which are similar to equations (9) and (10) are extracted from the circuit topology.

$$V_s = i_1(R_s + R_1) + L_1(i_1)\left[Z_{L_1u}i_1 + 2V^i_{L_1u}\right] + M_{12}(i_2)\left[i_2Z_{Lmu} + 2V^i_{Lmu}\right] + i_1Z_{Le1u} + 2V^i_{Le1u} \quad (15)$$

$$0 = i_2(R_2 + R_L) + L_2(i_2)\left[Z_{L_2u}i_2 + 2V^i_{L_2u}\right] + M_{21}(i_1)\left[i_1Z_{Lmu} + 2V^i_{Lmu}\right] + i_2Z_{Le2u} + 2V^i_{Le2u} \quad (16)$$

Figure 4: model of transformer with its Non-linear leakage inductance

Where Z_{Le1u} and Z_{Le2u} are primary and secondary side unit inductances of leakage inductances, V^i_{Le1u} and V^i_{Le2u} are leakage inductances distributed voltage. Leakage inductances between the two loops are calculated by using equation (17) and saved magnetic energy (w) in the loop.

$$W = \frac{\mu_0}{2}\iiint_v H^2 dV \quad (17)$$

This three-dimensional integral is reduced to a one-dimensional integral because the coils are the same height. The following assumptions have been considered:

H_1 : The magnetic field is parallel to the core axis.

H_2 : The magnetic field is symmetric with respect to the core axis.

Total winding leakage inductance is calculated by using equation (16):

$$W = \frac{1}{2}L_e i^2 \quad (18)$$

At the beginning of the simulation, it is assume that leakage inductance L_e is zero and terms in relations (17) and (18) that described characteristic of L_e (Z_{Le}) are replaced with zero. i_1 and i_2 are calculated by solving equations (13)-(15) and obtained values are used in equations (17) and (18).

$$i_1 = ((2M_{12}M_{21}V^i_{Lmu} + 2M_{12}V^i_{Le2u} + 2L_2M_{12}V^i_{L_2u})Z_{Lmu} + (V_s - 2M_{12}V^i_{Lmu} - 2V^i_{Le1u} - 2L_1V^i_{L_1u})Z_{Le2u} + (L_2V_s + 2L_2M_{12}V^i_{Lmu} - 2L_2V^i_{Le1u} - 2L_1L_2V^i_{L_1u})Z_{L_2u} + (R_L + R_2)V_s + (-2M_{12}R_L - 2M_{12}R_2)V^i_{Lmu} + (-2R_L - 2R_2)V^i_{Le1u} + (-2L_1R_L - 2L_1R_2)V^i_{L_1u}) / (M_{12}M_{21}Z^2_{Lmu} + (-Z_{Le1u} - L_1Z_{L_1u} - R_s - R_1)Z^i_{Le2u} + (-L_2Z_{L_2u} - R_L - R_2)Z^i_{Le1u} + (-L_1L_2Z_{L_1u} - L_2R_s - L_2R_1)Z_{L_2u} + (-L_1R_L - L_1R_2)Z_{L_2u} + (-R_L - R_2)R_s - R_1R_L - R_1R_2) \quad (19)$$

$$i_2 = ((M_{21}V_s - M_{12}M_{21}V^i_{Lmu} - 2M_{12}V^i_{Le1u} - 2L_1M_{21}V^i_{L_1u})Z_{Lmu} + (2M_{21}V^i_{Lmu} + 2V^i_{L_2u} + 2L_2V^i_{L_2u})Z_{Le1u} + (2M_{21}R_s + 2M_{21}R_1)V^i_{Lmu} + (2R_s + 2R_1)V^i_{L_2u} + 2L_2R_s + 2L_2R_1)V^i_{L_2u})) / (M_{12}M_{21}Z^2_{Lmu} + (-Z_{Le1u} - L_1Z_{L_1u} - R_s - R_1)Z^i_{Le2u} + (-L_2Z_{L_2u} - R_L - R_2)Z^i_{Le1u} + (-L_1L_2Z_{L_1u} - L_2R_s - L_2R_1)Z_{L_2u} + (-L_1R_L - L_1R_2)Z_{L_2u} + (-R_L - R_2)R_s - R_1R_L - R_1R_2) \quad (20)$$

Once that i_1 and i_2 are calculated, TLM voltages are also calculated and the process is repeated continuously. L_1 and L_2 in relations (17) and (18) are non-linear inductor, at each simulation time step their values change. Thus, M_{12} and M_{21} are also change within simulation because L_1 and L_2 changed [14]. The algorithm of simulation process will be briefly described in the following part.

Summary of the simulation process:

1. Define transformer parameters values, simulation time step (Δt) and start and end time of fault.

2. Investigating time (t):

2.1- If (Starting time of fault) > t or (ending time of fault) < t , then the primary and secondary current calculated by using equations (13) and (14).

2.2- If (Starting time of fault) < t or (ending time of fault)> t , then the primary and secondary current calculated by using equations (13) and (19).

3. Calculate the value of L_1 values in accordance with value of H shown in equation (20) and using BH curves (Figure 5)

$$H = \frac{N_1 i_1}{l} \quad (21)$$

4. Calculate values of L_2, M_1 and M_2 according to the previously calculated L_1 value and the transformer turn.

5. Calculated values of incident voltages from equations (9)–(11).
6. Save obtained results in this time step.
7. If t is lower than simulation time, go to step 2, otherwise go to next step.
8. Printing results stored during the simulation time including primary and secondary side current.

Specifications of used Transformer

To evaluate the performance of TLM method, this modeling approach applied on a sample Transformer with the following specifications: Single phase Transformer, $600VA$, $220/100$, $50HZ$, $B=T$. Primary side turn is 440 and secondary side turn is 230. Transverse plane of Transformer and windings is shown in Figure 5.

Figure 5: Transverse plane of Transformer

In TLM Analysis, it is assumed that the coupling coefficient k, between the inductors is the same in both side, it means that $k_{12}=k_{21}=k$. This assumption is valid because the Transformers structure is symmetrical according to its winding (two helix are identical by means of geometry).

The simulation for $k=0.98$ is performed in the following situation:

- No load condition without fault
- Under load condition without fault
- Study of magnetic inrush current
- Study of loop to loop short circuit fault on both sides
- Study of loop to ground short circuit fault on the secondary side.

For simulation of transformer’s early fault and limiting its fault current, resistor R_F (greater than zero) is placed at fault location. For example, Figure 6 had shown model of transformer with internal fault in the secondary side. Modeling relations that have been derived from figure 6, shown in the following part. Numbers which are in brackets in Figure 6 and 7 indicate the corresponding coil turns.

Figure 6: Short circuit at the secondary side between loops 150 and 160

For example, in Figure 6, in this term: $\left[(10)ZL_2+(10)2V^i_{L2}\right]$, 10 is Short circuit turn and the rest of the secondary side winding is 230 turn (150+10+70=230). Since the secondary side inductor (L_2) will change due to occurred fault, mutual inductance and leakage inductance are also changed during this condition. Once the fault is removed, the entire system returns to relations (17) and (18). Fault switch (FS) is used for internal faults. TLM model of Switch is also considered. A conventional method for modeling switch is a switch that has zero resistance when it is closed and has a large resistance in the open state. Disadvantage of this technique is that the network impedance matrix must be recalculated during each switch state. To overcome this, a model based on TLM is used. In implementing of this procedure, open switch modeled as a small capacitor and closed switched as a small inductor. Using this model lead to easier formulation and also ease solving of the circuit equations. In this case, the voltage of primary side is the same equation (13) and equation (14) is replaced by equation (19).

$$0=i_2\{(220)R_2+R_L\}+\{(150)L_2+(70)L_2\}\times \left[\left((150)Z_{L_2u}+(70)Z_{L_2u}\right)i_2+2V^i_{L_2u}\right] +M_{21}(i_1)\left[i_1Z_{Lmu}+2V^i_{Lmu}\right]+(i_2Z_{Le2u}+2V^i_{Le2u}) \quad (22)$$

Also more complicated model for studying internal short circuit in both side of transformer is used. The proposed model is shown in Figure 7. Short circuit fault is between turns 420 and 430 in primary side coil and between 150 and 160 turn of secondary side. For simplicity, a purely resistive load is connected to the secondary coil, thus secondary voltage and current have similar behavior. Secondary side voltage equation of TLM is defined by equation (20).

$$V_s=i_1\left(R_s+(420)R_1\right)+(420)L_1(i_1)\times \left[(420)Z_{L_1u}i_1+(420)2V^i_{L1u}\right]+(420)M_{12}(i_2)\times \left[i_2Z_{Lmu}+2V^i_{Lmu}\right]+(i_1Z_{Le1u}+2V^i_{Le1u}) \quad (23)$$

Equations (19) and (20) are re-solved to obtain i_1 and i_2. Then these currents values are used to calculate two parameters of TLM and magnetic field density (H).

Figure 7: internal Short circuit on both sides

H is easily calculated by (24) then the value of B calculated by using BH curve and also μ_r is calculated by Relation of B and H. Finally, primary side winding Inductor (L_1) is calculated and by using transformer ratio, secondary side winding inductor (L_2) is obtained.

$$\frac{N_1I_1}{length} \quad (24)$$

Simulation Results

no-load conditions without fault

In case of no-load, drawn current is mainly devoted to power losses and core magnetizing, in this state Transformers behave as a large inductor. Due to nonlinear BH curve and hysteresis, the transformer current is not sinusoidal exactly, can be seen in Figure 8.

Figure 8: Transformer primary side current in no load condition

Under load condition without fault

Figure 9 shows Transformer primary and secondary side current. In this case, 250 ohms resistor is used as load. Unlike figure 8, the current is nearly sinusoidal. Of course, this does not mean that hysteresis characteristic of core is wasted, this happens due to ohmic load of the secondary side.

Figure 9: primary and secondary current in loading condition

Magnetizing inrush current

In this case, it is assumed that Transformer is turned on at time of 0. This state Simulation result is shown in Figure 10. All initial values are zero in TLM simulation. As it is expected, amplitude of inrush current (current which is drawn at starting point and used for magnetizing transformer core) is greater than nominal current and also has transient DC offset. Transient DC offset means damping state which is affected on current curve at starting point.

Figure 10: magnetizing inrush current

Winding’s loops short circuit on both side

Loop short circuit fault is discussed and its effect on the primary and secondary side current is investigated. BH curve of transformer is shown in Figure 11. When fault occur in primary side, primary current increase a little but secondary side current does not change. Nevertheless, short circuit eddy current flow in short circuited loops.

Figure 11: Transformers BH curve used for TLM simulation

Loop short circuit fault on the primary side started at 0.3s and ended at 0.4s between loops 420 and 430. In this case Transformer is loaded with holmic resistor. When the time is about 0.3s equation 13 is substituted with 19 to simulated short-circuit conditions. After removing primary side fault (in 0.4s) again equation 13 used to simulate normal conditions. side

Figure 12: Primary and secondary side current with a fault in secondary side

Figure 13 shows primary and secondary side in state that fault occurs between loops 150 and 160 in secondary side between 0.3s and 0.4s. Same as previous state, before fault happen simulation is based on equations (13) and (14), during the fault equations 13 and 14 replaced by equations 19 and 20. After removing fault of primary side (.3s), again equation 13 is used to model. For modeling fault and limiting eddy current, a 1Ω resistor is used.

Figure 13: loop to ground fault at primary side

Loop to ground fault on secondary side

In this case, loop 200 of secondary side coil is connected to ground. Figure 14 shown primary current in this mode. Amplitude of primary current in this state is greater than the one with loop to loop fault and primary current also has transient mode at starting point, this means that current have dc offset. Increase core magnetic field (saturation of core), deform its sinusoidal shape. Magnetic field increase in this mode is greater than the one with loop to loop fault because voltage between loops to ground is higher than loop to loop one, therefore short circuit current which transmit through magnetic coupling is also greater. So this kind of fault could be detected bye monitoring primary current of transformers.

Figure 14: primary current with loop to ground fault on the secondary side

Conclusion

In this paper, a new approach is proposed for modeling transformers internal faults by using TLM that accurately detect Transformers conditions (such as no load, under load, switching transient mode).This modeling technique could be used for two windings Transformers to obtaining Transformers transient transmitted power value which is useful for testing and developing of protection relay. It should be noted that this method can be easily applied to single-phase or three-phase Transformers with any power. This study used a single phase Transformer because single phase Transformer data availability. The advantage of this method is that it can simulate loop to loop and loop to ground faults and etc between the desired Transformer's loops and recorded the results to compare with real Transformer to detect its condition. Transformers TLM model for the study of internal faults based on Transformers physical data is implemented with Matlab software. According to the simulation results, it is verified that the proposed modeling technique for studying and detecting short-circuit conditions of Transformers is accurate. In general, primary and secondary voltages do not significantly change during internal faults (only a small change happened when fault is in the secondary side). Therefore, this kind of error can not be detected by monitoring voltages and current samples must be used for this purpose.

Nomenclature

TLM~ Transmission Line Model
L~ Inductor
C~ Capacitor
M~ Mutual Induction Factor
R~ Resistor
R_F~ Fault Resistor
V_L~ Inductor Voltage
I_L~ Inductor Current
BH~ Magnetization Curve

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