Transformer Internal Incipient Fault Simulations

Mirrasoul J. Mousavi, IEEE Student Member, Karen L. Butler-Purry, IEEE Senior Member

Abstract—Transformer fault detection and diagnosis is becoming more important due to the restructuring of the electric power industry. In this era of deregulation, loading transformers to their optimum capacity is becoming normal practice, which in turn applies high stresses on the insulation of the transformers and increases the probability of occurrence of internal incipient faults. Such faults can lead to a catastrophic failure and hence cause outages. Utilities and other entities in the electric power business are therefore exploring ways of detecting these faults in transformers in the incipient stage. Terminal values, primary and secondary currents and voltages, convey information that can be used to detect transformer incipient faults. In an effort to characterize the behavior of the terminal values of a transformer during internal incipient faults, computer models were developed. This paper briefly reviews the models and discusses simulation results obtained using SIMPLORER® software package. It also presents a discussion of the influence of model parameters on the terminal values and provides suggestions on tuning them appropriately to achieve simulation data for various incipient fault scenarios. Finally, the simulation methodology was verified by a field recording of a secondary winding incipient fault.

Index Terms—Transformer, Internal incipient faults, Modeling and simulation.

I. INTRODUCTION

Reconstructuring in the power industry has triggered several structural changes in the electricity market, which has required the electric utilities to reduce operating costs while enhancing the supply of power and services to customers. Utilities are therefore exploring various possibilities for optimizing usage of existing electrical equipment such as transformers. The main driving forces are to shift from a scheduled to condition-based maintenance, prevention of forced outages with the related consequential costs, and the operation of equipment closer to their ratings without compromising reliability, longevity and integrity.

A study of the records of modern transformer breakdowns, which occurred over a period of years, shows that between 70%-80% of the number of transformer failures are eventually traced to internal winding faults [1]. These winding faults are mostly a result of the degradation of the insulation system due to various thermal, electrical, mechanical stresses, moisture and so on. Degradation means reducing insulation quality, which will eventually cause a breakdown in the insulation. It either leads to adjacent turns shorted to the earth (turn-to-earth short circuit fault). Most often the insulation undergoes a gradual aging process before such a short circuit fault happens. During this period, which is called an incipient fault, the electrical properties of the insulation alters adversely and incipient-like behavior commences. Incipient faults may convey non-periodic, asymmetric and sporadic arcing currents, which are random in magnitude and could involve sporadic bursts as well. It is well known that an initial incipient fault does not draw sufficient current from the line to operate protective devices. As the fault becomes more severe, it is important to detect it before a catastrophic failure happens.

Ongoing research at Texas A&M University aims to develop an incipient fault detection method for transformers. One of the major initial tasks was to generate fault data for the characterization of the internal incipient faults. From the fault data, it would be possible to explore the terminal behavior of the transformer, which includes primary and secondary voltages and currents, during such faults. Unique characteristics derived from this data would be then used as the basis in developing a transformer incipient fault detection method. In order to obtain incipient fault data, the models proposed in [2] were utilized to simulate various incipient fault scenarios at different degradation levels of the transformer winding insulation. The models were implemented using commercially available software called Ansoft SIMPLORER® (version 6.0) [3]. This software package provides appropriate tools and features to simulate and analyze complex systems. One can create simulation models quickly, process simulations accurately and reliably with the simulator backplane technology, and transfer the simulation data and result presentations to other applications.

This paper presents a description of the incipient fault computer models and discusses simulation results of internal incipient faults performed on a computer model of a distribution transformer. It also illustrates the model parameter’s effect on the terminal values and provides suggestions on the tuning of these parameters for different fault scenarios to achieve the best similarity between simulation and field results.

This paper is organized as follows. Section II provides a quick review of the transformer internal incipient fault model. In section III, the implementation procedure is discussed. Section IV gives a thorough discussion of the results. Conclusions are given in section V.

II. TRANSFORMER INTERNAL INCIPIENT FAULT MODEL

The transformer internal incipient fault computer model is a combination of a two-dimensional nonlinear finite element analysis internal short circuit fault model and deteriorating
insulation model consisting of an aging and an arcing component. These models are briefly reviewed in this following section. More details about these models can be found in [2,4].

A. Transformer Non-Linear Model

The transformer two-dimensional nonlinear finite element model presented in [5] applies finite element analysis to calculate the parameters for an equivalent circuit of a transformer with an internal short circuit fault. Ansoft Maxwell® software package was used to perform calculations. The transformer model can be exported as a SPICE sub-circuit and imported to the SIMPLORER® simulation environment as a black box with a set of interface terminals. These terminals are appropriately connected to the voltage source, load, and incipient fault model to simulate an incipient fault scenario.

B. Aging Model

The aging model is traditionally represented by an equivalent parallel RC network as shown in Fig. 1. In the circuit, \( R_p \) represents the lossy part of the dielectric, which results from electronic and ionic conductivity, dipole orientation and space charge polarization, etc.; and \( C_p \) is the capacitance in the presence of the dielectric [6]. In Fig. 1(b) the corresponding phasor diagram of the equivalent circuit is shown. Angle \( \delta \) is defined as the loss angle, which represents the dielectric energy losses in the insulation. Tan \( \delta \) is commonly known as the loss tangent or dissipation factor. The loss angle is usually very small for perfect insulation. It differentiates the losses in one dielectric material from those in the other one. Cos \( \theta \) is the power factor of the dielectric. Equation (1) expresses the relationship between circuit elements and the dissipation factor. When an AC voltage is applied, the capacitive component of the current is \( I_c \) while the resistive component of the current is \( I_R \).

\[
\tan \delta = \frac{1}{\omega R_p C_p} \tag{1}
\]

\( a \) Parallel equivalent circuit \hspace{1cm} \( b \) Corresponding phasor diagram

Fig. 1. Equivalent circuit of insulation

Under operating conditions of voltage and temperature, an insulating material may deteriorate in electric strength because of the absorption of moisture, physical changes of its surface, chemical changes in its composition, and the effects of ionization both on its surface and on the surface of internal voids. In general, the dissipation factor will be increased. With a proper understanding of the effects of aging factors, the changes in any electrical property, particularly dissipation factor, can be a measure of deterioration [7]. While the initial value of dissipation factor is important, the change in dissipation factor with aging may be much more significant.

In this work, the insulation between adjacent turns of winding is assumed to be a solid insulation of type NOMEX® which is a synthetic aromatic polyamide polymer, widely used in transformers, motors, generators, and so on. The different degradation levels of the insulation were modeled by varying the dissipation factor. The corresponding equivalent circuit parameters namely, the resistance and the capacitance for adjacent turns were calculated as follow. First, the maximum voltage between the adjacent turns of primary or secondary winding was estimated by (2).

\[
V_t = 2 \cdot \frac{V_{m}}{N_w^2} \tag{2}
\]

\( V_w \) is the maximum voltage across the winding and \( N_w \) is the number of turns of the winding. Then the voltage \( V_t \) was applied to the insulation sample as shown in Fig. 2. Using finite element analysis, the energy \( U \), stored in the insulation, was calculated. Then the capacitance was calculated based on the geometry information and the material properties of the insulation using (3).

\[
C_p = \frac{2U}{V_t^2} \tag{3}
\]

Fig. 2. Diagram for insulation sample

After calculating \( C_p \), a reasonable dissipation factor representing a particular degradation level of the insulation was chosen. Since the equivalent capacitance does not change much, the resistance in the equivalent circuit can be calculated by manipulating (1) for different dissipation factors. For instance, Table I shows the calculation results for perfect insulation between adjacent turns. According to the manufacturer specification for the type of the insulation assumed in this work, the dissipation factor for the perfect insulation is 0.006. When \( m \) turns are involved in the primary or secondary incipient fault, the equivalent circuit parameters \( R_{pm} \) and \( C_{pm} \) were calculated by (4) using the equivalent circuit parameters for adjacent turns.

\[
R_{pm} = R_p \cdot m, C_{pm} = C_p / m \tag{4}
\]

<table>
<thead>
<tr>
<th>Winding</th>
<th>( V_t ) (Volts)</th>
<th>( U ) (uJ)</th>
<th>( \tan \delta )</th>
<th>( C_p ) (uF)</th>
<th>( R_p ) (Mohm)</th>
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</thead>
<tbody>
<tr>
<td>Primary</td>
<td>26.1</td>
<td>122.58</td>
<td>0.006</td>
<td>0.3599</td>
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</tr>
<tr>
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<td>26.1</td>
<td>50.00</td>
<td>0.006</td>
<td>0.1468</td>
<td>3.01</td>
</tr>
</tbody>
</table>

C. Arcing Model

A persistent fault in a transformer would eventually involve an arc which is defined as a continuous luminous discharge of electricity across an insulating medium, usually
accompanied by the partial volatilization of the electrodes [8]. The arcing characteristics can be illustrated as in Fig. 3. This is a simple case where arcing happens in a resistive load circuit. The arc ignites only after sufficient voltage is across the gap. This period is called the burning period. Arcing voltage is almost a square wave, except for the transient near current zero. In addition, arcing is a random and stochastic phenomenon. The arc extinguishes when voltage drops below that needed to sustain the arc. This period (Δt in the figure) of effectively zero current around the virtual zero point of the sinusoid is called the extinction period. The characteristics of an arcing current have to be considered in the simulation model to obtain a representative circuit that can take the place of the arc thereby obtaining accurate analysis results. But, of course, it is known that the arc is by no means a simple circuit element [9].

For the purpose of modeling arcing phenomena between adjacent turns of the transformer, where the arc gap is very small, the circuit shown in Fig. 4 can be used. The voltage E is a random square wave representing the equivalent arcing voltage in the burning period. It has been shown that the arc voltage is usually flap-topped and that the magnitude of arcing fault currents ranged from 57% to 100% of the available short-circuit current. During periods of effective current zero, however, arc can be represented by a high nonlinear resistance, R(t), which increases with time. When arcing is in the burning period, switches S1 and S2 control the burning and extinction period of an arc, respectively. When arcing is in the burning period, S1 is closed and S2 is open. In the extinction period, S2 is closed and S1 is open. Otherwise, both switches are open.

**D. Comprehensive incipient fault model**

A complete internal incipient fault model for the transformer can be obtained by connecting the aging and the arcing model in parallel or in series [4]. The appropriate series combination is shown in Fig. 5. Each of these circuit combinations conveys incipient fault characteristics from different points of view. Therefore, depending upon the simulation scenario, the series or parallel combination may be used to obtain data. Various features related to these combinations will be thoroughly discussed in section IV.

III. INCIPIENT FAULT MODEL IMPLEMENTATION

Simulations were carried out on a single-phase, 7200V/240V/120V, 25kVA, and 60 Hz distribution transformer. Table II shows the transformer terminal peak values based on given specifications at rated power. The primary winding had 780 turns and the secondary winding had a total of 26 turns, 13 turns per winding. This specification is the same as that of the custom-built transformer used for internal short circuit field experiments [10]. The custom-built transformer was equipped with various taps placed on both windings so that internal faults could be staged. The insulation between the layers was made of NOMEX® paper.

<table>
<thead>
<tr>
<th>Index</th>
<th>Parameters</th>
<th>Rated Peak Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Primary voltage (v)</td>
<td>10080</td>
</tr>
<tr>
<td>2</td>
<td>Secondary voltage (v)</td>
<td>336</td>
</tr>
<tr>
<td>3</td>
<td>Primary current (A)</td>
<td>4.86</td>
</tr>
<tr>
<td>4</td>
<td>Secondary current (A)</td>
<td>145.83</td>
</tr>
</tbody>
</table>

The simulation circuit diagram developed with ANSOFT SIMPLORER® is shown in Fig.6. It represents an incipient fault on the secondary winding of the transformer and comprises four layers as numbered on the figure.

Layer one is the power circuit including the transformer finite element model imported from ANSOFT MAXWELL®, upstream network Thevenin equivalent circuit represented by Vc and Rc, and a constant impedance load model. Vc was assumed to be 7200 volts (rms) and Rc was chosen as 10 mΩ. The transformer load was chosen as a resistive load of 2.304Ω in all simulations. Measuring instruments were placed on the primary and secondary sides of the transformer to measure the terminal values and the circulating current.

Layer two is the incipient fault model including the aging model and the arcing model. It is connected to the terminals
of part of the secondary winding, which is involved in the fault. Time-controlled switches were placed at several locations to simulate short circuit and/or incipient fault scenarios at different initiation times. This was accomplished by incorporating STEP functions as switch controlling signals.

Layer three consists of control blocks whose function is mainly to provide the arcing voltage based on the system voltage across the turns involved in the incipient fault. The system voltage was fed to two comparators with a user-defined threshold value. This threshold value depended on the number of turns involved in the fault and the voltage gradient. The outputs from these comparators were either zero or a constant value. Then, they were added together and multiplied by a sequence of 0’s and 1’s generated by a random number generator block at each half cycle. The multiplier output is a random square waveform that constitutes the arcing voltage.

With SIMPLORER’s state graph (machine), discontinuous processes can be modeled as event-oriented operations. A process sequence can be considered as a sequence of states. Switching the activity from states to their successor states is called an event. At the beginning of the simulation, one state must be defined as active. Three state graphs were used in layer four to determine the arcing voltage initiation time and to simulate the non-linear resistance during extinction period as a controlled non-linear current source. The first state machine determines arcing voltage initiation time based on whether the arcing model is in effect or not. State machine II controls the sign of the current by looking at the derivative of the arcing voltage to determine whether it should be positive or negative. State machine III provides a short time-signal (Δt in Fig. 3) to simulate the decaying current during the extinction period. It determines the leading edge of the voltage and increments the time by the step size to constitute the time signal. The signal is reset to zero when the extinction period ends.

To simulate an incipient fault scenario using the above circuit, the following steps are taken before running the simulation. One, the corresponding FE transformer model is imported and assigned to the transformer block at layer one. Two, the number of turns involved in the fault is entered in the constant block at layer three. Three, simulation parameters such as, maximum simulation time, step size and maximum step size are set according to the simulation scenario. Lastly, incipient fault model parameters are set.

IV. SIMULATION RESULTS

Using the simulation circuit, various studies were performed, which are discussed in the following sections. Even though, most of the figures were related to secondary fault cases, primary winding faults were also simulated similarly. In fact, conceptually there are no differences between simulating primary faults and secondary winding faults. The following procedure was followed for a primary fault case. Firstly, the corresponding FE transformer non-linear model was imported and assigned to the transformer block. Secondly, the necessary changes were made to the connectivity scheme of the transformer terminals to represent a primary fault case. Lastly, the aging and arcing model parameters were tuned accordingly.

A. Evaluation of Series and Parallel Combination of the Aging and Arcing Models

1) Simulated Incipient Fault Using Parallel Combinations

Fig. 7 illustrates the terminal values during an incipient fault between the 2nd and 4th turns of the secondary winding (s2_4 fault case). The parallel combination of the insulation model was used in this case. The parallel resistance, \( R_{\text{par}} \), was chosen as 0.01\( \Omega \) and the corresponding equivalent capacitor was obtained as 0.0734 \( \mu \text{F} \) from Table I and (4). The voltage threshold was 70% of the peak turn-to-turn voltage. Four scenarios namely, normal, aging, arcing and short circuit were simulated consecutively as shown on the primary current graph in Fig. 7. The first two cycles show the terminal values when the insulation is in perfect condition and the transformer is loaded nominally. This implies that no aging or arcing model is in effect. The nominal peak values conveyed by the figure are in agreement with those given in Table I.

Beginning with the third cycle, at time 33.33 ms, the transformer underwent an advanced insulation deterioration, which was simulated by switching the aging model on. Comparing with the previous normal condition, the primary current increased, and the secondary current and voltage decreased slightly. The primary voltage did not change much since it is biased by the Thevenin voltage of the upstream network. The amount of changes in the terminal values directly depends on the severity of the aging or the degradation level of the insulation represented by \( R_{\text{pm}} \) in the simulation model. The aging activity was later accompanied by the arcing current at the end of the forth cycle, at time 66.66 ms. As seen in the figure, the arcing happened randomly in the positive half cycle, negative half cycle or both. The peak primary current when arcing occurred was considerably larger than that of the primary current with
aging model only. Moreover, the waveform was not sinusoidal. A combination of the aging and arcing current finally caused the insulation to break down and an internal short circuit current flowed at time 0.20 seconds. The magnitude of the primary current was large enough to be detected by the protective devices. The decrease in the secondary voltage and current waveforms was distinguishable in this case.

Fig. 7: Terminal values of the transformer during a secondary incipient fault (s2_4) using parallel combination model

Fig. 8 illustrates variations of the turn-to-turn voltage and circulating current flowing through the insulation during s2_4 fault scenario. The turn-to-turn voltage as predicted by the model is a sinusoidal waveform during the no-arcing period and a flat-topped semi-square waveform when arcing occurs. The behavior of the circulating current is very similar to the primary current shown in Fig. 7, except that the magnitude of the current is much higher than that of the primary current.

It should be noted that as far as time is concerned, the above fault scenario does not represent an actual fault development in that incipient fault progress is a gradual process that might take days, weeks or years to lead to a short circuit fault, depending on the level of contribution of the aging factors. However, the characteristics represented in the figure are similar to what might be seen during the various fault stages.

2) Simulated Incipient Fault Using Series Combination
The same incipient fault scenario was simulated with a series combination of the aging and arcing models. The parallel resistance, $R_{parallel}$, was chosen as 1mΩ and the corresponding equivalent capacitor was the same value of 0.0734 µF. The voltage threshold was 70% of the peak turn-to-turn voltage. Figs. 9 and 10 illustrate the terminal values, the circulating current and turn-to-turn voltage. From the primary current, it is seen that arcing current occurs randomly in each half cycle and the peak current during the arcing period is smaller than the short circuit current level. During the no arcing period, however, the primary current changes normally and the circulating current is effectively zero. Due to relatively small circulating current during the arcing period, the other terminal values have not been affected much. By changing the aging resistance, the arcing current can be readily controlled. Moreover, the arcing voltage threshold is an effective factor in determining the peak values.

Fig. 8. Circulating current and turn-to-turn voltage during a secondary incipient fault (s2-4) using parallel combination model
3) Performance Comparison of Series and Parallel Combinations

Simulations of other fault scenarios on both primary and secondary windings led to the following conclusions about the parallel combination of the models. When the aging and arcing models are in parallel, they essentially act independently. The aging resistance controls the aging current and the arcing voltage threshold dictates the arcing current. In other words, for different aging levels, the peak arcing current remains constant if the arcing threshold is fixed. Moreover, the arcing current magnitude is relatively large enough to be detected by the protection system whereas incipient faults do not draw sufficient currents to trigger the protection system.

The series model, however, provides a better way to control arcing current magnitude than the parallel model. Since the aging resistance is in series with the arcing circuit, the arc current is effectively limited by the value of the resistance. This physically implies that the arcing activity is controlled by the degree of deterioration, which is a valid inference. Moreover, by varying the arcing threshold from 50% to 100% of the system voltage, various arcing magnitudes can be achieved. The range of variations is not large compared with the parallel combination range of variations. Furthermore, it will be shown in the next sections that using the series combination, a similar behavior to field experiments can be achieved.

A turn-to-turn fault on the secondary winding is seen as an ordinary double winding load on the primary side. When an incipient or a short circuit fault happens on the secondary winding of the transformer, the primary current tends to increase, the primary voltage decreases very slightly, and the secondary current and voltage decrease simultaneously for a resistive load. On the other hand, if the fault occurs on the primary winding, the turns involved in the fault act as an autotransformer load on the winding. In this case, the primary current increases, the primary voltage changes very slightly, and the secondary values remain unchanged. The amount of change for either case, however, depends on the number of turns involved in the fault and the degradation level of the insulation. This behavior is in agreement with the experimental results reported in [4].

Fig. 9. Terminal values of the transformer during a secondary incipient fault (s2-4) using series combination model

A turn-to-turn fault on the secondary winding is seen as an ordinary double winding load on the primary side. When an incipient or a short circuit fault happens on the secondary winding of the transformer, the primary current tends to increase, the primary voltage decreases very slightly, and the secondary current and voltage decrease simultaneously for a resistive load. On the other hand, if the fault occurs on the primary winding, the turns involved in the fault act as an autotransformer load on the winding. In this case, the primary current increases, the primary voltage changes very slightly, and the secondary values remain unchanged. The amount of change for either case, however, depends on the number of turns involved in the fault and the degradation level of the insulation. This behavior is in agreement with the experimental results reported in [4].

Fig. 10. Circulating current and turn-to-turn voltage during a secondary incipient fault (s2-4) using series combination model
B. Incipient Model Parameter Tuning

1) Influence of the Resistance in the Aging Model (R_{pm}) on the Terminal Values

To investigate the effect of the resistance on the terminal values for a particular fault scenario, no arcing activity was included in the model during the fault simulation. The resistance value was varied from 1K\Omega to 10 \mu\Omega. The variation of the resistance spans the lifetime of the insulation from a nearly perfect insulation to completely deteriorated one. The corresponding equivalent capacitor remained unchanged as 0.0734 \mu F. Fig. 11 represents the relationship between the peak terminal values of the transformer in one power cycle and the resistance R_{pm} when the incipient fault happens -in particular- between the second and the forth turns on the secondary winding. Note that the horizontal axis is logarithmically scaled. From the plots, the following conclusions are obtained. When R_{pm} is larger than 0.1 \Omega, the terminal values are very close to the rated values indicating that the transformer is still in good condition. However, when R_{pm} is less than 0.0001 \Omega, the terminal values are approximately equal to the values when an internal short circuit fault occurs. When the value of R_{pm} is in the range of [0.1, 0.0001] \Omega, the terminal values change between the rated values and the short circuit quantities. Simulations showed that the range of [0.1, 0.001] \Omega was appropriate enough to simulate other incipient fault scenarios on the secondary winding. On the other hand, the suitable range of variations for the aging resistance for primary faults was obtained to be [500, 0.01] ohms. To obtain this range for primary winding faults, the similar approach that was used for secondary fault cases was taken.

2) Influence of Arcing Voltage Threshold on the Terminal Values

It is mentioned in the literature that the arcing voltage at lower voltages is a flat-topped waveform, however the magnitude of the voltage at which the arcing current flows has not specifically been determined. Instead, what is known is that for the arcing current to flow through the insulation, the arc gap has to be broken down under a sufficiently high voltage. Therefore, in practice, the arc voltage at the beginning of each half-cycle is considerably higher than that at its end [9]. To investigate the effect of arcing voltage magnitude on the terminal values, simulations were performed with the arcing model where the arcing voltage threshold was varied discretely from 50% to 100% of the existing turn-to-turn voltage. In obtaining the results, the simulations were performed for each voltage threshold value while the other parameters remained unchanged. The aging model was effectively disconnected by choosing a large value for the resistance in the aging model.

The results of simulations show that the voltage threshold value affects the primary current more than the others. As the voltage threshold increases, the primary current decreases, whereas the other terminal values increase slightly. As a result, the higher the voltage threshold, the lower the increase in the primary current. In simulating an incipient fault case, the threshold value changes randomly from 50% to 100% of the existing turn-to-turn voltage. This range of variations covers possible situations in which a real incipient fault can initiate an arcing current between the turns involved in the fault.

![Fig. 11. Relationship between terminal values and resistance in the aging model of the transformer during a secondary incipient fault (s2-4)](image-url)

C. Simulation Results Compared with Field Experiments

The characteristics from a filed test recording were compared with the characteristics obtained from the simulations. The recording was obtained during the last set of short circuit experiments on a custom-built distribution transformer described in section III. After performing numerous internal short circuit experiments on the
Transformer over a 19-month period, incipient-like behavior seemed to be present in the field tests. It is believed that as a result of such short circuit faults, some of winding turns lost their integrity and became deteriorated. The first fault scenario in which arcing apparently was shown was a secondary fault.

An experimental recording of the incipient fault between the 10th and 13th turns of the secondary winding of the transformer is shown in Fig. 12. It includes the terminal currents and the circulating current. At the normal condition, the peak value of the primary current was around 5A, and the secondary current was 150A. The primary current for an internal short circuit fault between turns 10 and 13 of secondary winding was measured to be 30 A. However, in this case, after incipient fault initiation at 28.75 seconds, the peak primary value varied between 10 to 12A indicating the aging accompanied by the arcing activity between the turns. This amount of increase in the primary current is not high enough to trigger the protection system with normal pick-up current. From the figures, it is also clear that arcing occurs randomly. From the secondary current figure, it is seen that during the time when arcing occurs, the current peak decreases, which indicates that the insulation on the secondary winding is degrading. The circulating current also conveys large random spikes, which becomes zero when there is no arcing activity. It reaches 1500A at the highest arcing current activity.

The same incipient fault scenario was simulated with the proposed methodology using the series combination of the aging model and arcing model. The parallel resistance in the aging model was set to 0.01Ω and arcing voltage was varied randomly from 50% to 90% of the system voltage. The results are shown in Fig. 13. Comparing this figure with field results shown in Fig. 12, similar characteristics in terms of randomness and magnitude of the currents during the no-arcing period and arcing period are observed. This verifies the simulation results obtained with the series combination model. Moreover, the different aging levels can be achieved by varying the resistance in the aging model. However, because the arcing activity is a random process, the field experiments and simulation results follow a different arcing sequence and do not coincide at the time domain.

V. CONCLUSIONS

Transformer internal incipient fault simulations include incorporating a deteriorating insulation model, which consists of an aging and an arcing component. This paper presented the implementation and results of simulations of various incipient fault case using SIMPLORER® software. It addressed the influence of model parameters on the terminal values of the transformer and suggested hints and comments on tuning them to simulate different fault scenarios. Furthermore, the advantages and disadvantages of using two methods of combining the aging and arcing models were illustrated and it was concluded that the series combination provided realistic results compared with field experiments.

The range of [0.1,0.001]Ω was obtained for the resistance in the aging model to simulate secondary winding insulation at different deterioration levels. For primary winding insulation, however the suitable range of variations of the aging resistance was obtained to be [500,0.01] ohms. It was observed that the threshold value for the arc to initiate affected the primary current more than the other terminal values for a fault on the primary and secondary winding. As the voltage threshold increased, the primary current decreased, whereas the other terminal values increased slightly. As a result, the higher the voltage threshold, the lower the increase in the primary current.

Finally, if an incipient fault occurs on the secondary winding of the transformer, the primary current tends to increase, the primary voltage decreases slightly, and the secondary current and voltage slightly decrease simultaneously for a resistive load. On the other hand, for an incipient fault on the primary winding, the primary current increases, the primary voltage changes slightly, and the secondary values remain unchanged. The amount of change depends upon the number of turns involved in the fault and the degradation level of the insulation. Future work includes generating fault data with simulations of the computer model and identification of the characteristics of such faults through advance digital signal analysis techniques.
Fig. 13. Terminal currents and circulating current during a simulated incipient fault between the 10th and 13th turns on the secondary winding

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REFERENCES


BIOGRAPHIES

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