Modeling and Simulation of the Power Transformer Faults and Related Protective Relay Behavior

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***Abstract*—The modeling of power transformer faults and its application to performance evaluation of a commercial digital power transformer relay are the objective of this study. A new method to build an EMTP/ATP power transformer model is proposed in this paper. Detailed modeling of the transformer relay is also discussed. The transient waveforms generated by ATP under different operating conditions are utilized to evaluate the performance of the transformer relay. The computer simulation results presented in this paper are consistent with the laboratory test result obtained using an analog power system model.**

***Index Terms*—Analog power system model, digital relay modeling, electromagnetic transients program, power transformer modeling.**

I. Introduction

COMPUTER simulation of power systems and protective re- lays eases the burden of relay testing and relay performance evaluations. This new technology draws a lot of attention from industry, and is now becoming widely adopted [1].

The main directions in the computer modeling for the study of the power transformer electromagnetic transients are summarized in [2]. The simulation results presented in [3] show that hysteresis does not add to the damping of the inrush currents. The eddy currents provide appropriate damping effects in the simulation of transients as determined by the underlying physical phenomena, but the eddy current damping is insignificant in the fast transient study [4]. Based on the above observation, the modeling of hysteresis losses and eddy currents is not considered in the modeling of the power transformer in this paper.

Degeneff *et al.* used lumped R-L-C circuit to represent transformer winding [5]. This method requires knowledge on the details of the transformer construction to get these parameters, and these parameters are very difficult to estimate from an external testing.

In [6], a method to establish a multisection network model for study of high frequency transient behavior of the transformer and machine winding is presented. The winding with equally divided sections is considered in this paper. That will make the number of sections be large if this method is used for simulating the small turn-to-turn fault of transformer. Another problem is that only the single winding is studied in this paper.

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A method to calculate the coupled RL parameters of the split winding is proposed to simulate the turn-to-turn fault in [7]. Implementation of this method assumes detailed knowledge of the parameters of the winding structure. These parameters are very difficult to obtain from the transformer manufacturer.

In this study, a power system source is modeled by EMTP/ATP (ATP is the royalty-free version of EMTP) first. Then a new method to model the single phase transformer with 3 winding in this power system is explored. The least error squares estimation method is applied to estimate the power transformer parameters. This information is used to simulate power transformer internal winding fault by utilizing EMTP [8]. The transformer studied is modeled as a coupled RL circuit, and these parameters are estimated from the measurement using testing on actual winding. This new model is verified by comparing the EMTP/ATP simulation results and the waveforms recorded from a power system model in a laboratory. The detailed modeling of a current differential transformer relay is also discussed. The simulation for a special case, transformer turn-to-turn fault involving inrush current, is used to illustrate how the proposed transformer modeling benefits the power transformer protection performance evaluation. The conclusions are drawn at the end.

II. Modeling of the Power Sources

A digital power transformer protection system (WBZ-500) has been in development since 1988 at Huazhong University of Science and Technology (HUST), China, and now it is being commercialized. The power system model in the Electrical Power Dynamic Laboratory (EPDL) at HUST was used in the development of WBZ-500. The one-line diagram of this test system is shown in Fig. 1. In this system, the power transformer consists of three single-phase power transformers. Its winding configuration is $Y/Y/\Delta$. There are two types of power sources: one is the so called the “infinite bus,” connected from the high voltage power system by a step-down transformer; the other one is a 15 KVA synchronous machine.

For the “infinite bus” power source, type-51, 52, 53 cards of EMTP/ATP can be used to model the equivalent internal impedance of the infinite bus supplied by an ideal balanced three phase voltage source. The sequence impedances are measured as:

$$\begin{cases} Z_1 = 26.55\angle 76.3\ \Omega \\ Z_0 = 16.56\angle 74.8\ \Omega. \end{cases} \tag{1}$$

For the modeling of the generator, the transient caused by the fault in a short period of time is of major concern. Therefore, the generator can be modeled adequately as an equivalent voltage sources E'' behind subtransient inductances ($X''_d = 0.88\ \Omega$) for high speed relay testing.

After comparing the ATP simulation result and test waveform recorded by a digital fault recorder (DFR) in EPDL, it is found that the two models are fairly accurate in describing the transient of these two power sources.

III. The Model of a Single Phase Transformer with 3 Windings

A method which only uses the test data measured externally to estimate the parameters of the coupled RL network is proposed in this paper. The implementation of this method is discussed in this section.

The three single phase transformer configuration is widely used in the high rating transformer. This single phase transformer can be represented by $\boldsymbol{R}$ and $\boldsymbol{L}$ matrices, which in turn can be obtained from the excitation and short-circuit test data by means of the BCTRAN auxiliary program in EMTP/ATP [8].

In this case, $\boldsymbol{R}$ and $\boldsymbol{L}$ are 3 × 3 matrices:

$$\boldsymbol{R} = \begin{bmatrix} R_1 & 0 & 0 \\ 0 & R_2 & 0 \\ 0 & 0 & R_3 \end{bmatrix}, \qquad \boldsymbol{L} = \begin{bmatrix} L_1 & M_{12} & M_{13} \\ M_{21} & L_2 & M_{23} \\ M_{31} & M_{32} & L_3 \end{bmatrix}$$

where R_i and L_i are the resistance and self inductance of the winding i, and M_{ij} is the mutual inductance between the windings i and j. In the BCTRAN, the magnetic asymmetry is not taken into account, so $\boldsymbol{R}$ and $\boldsymbol{L}$ are symmetrical matrices.

Once $\boldsymbol{R}$ and $\boldsymbol{L}$ matrices are calculated, two types of winding faults are considered: turn-to-ground and turn-to-turn. The principle of modeling these faults is to modify $\boldsymbol{R}$ and $\boldsymbol{L}$ matrices accordingly.

A. The Turn-to-Ground Fault Mode

Assume the high voltage side has a turn-to-ground fault shown in Fig. 2. Then this transformer can be described with two 4 × 4 $\boldsymbol{R}$ and $\boldsymbol{L}$ matrices:

$$\boldsymbol{R} = \begin{bmatrix} R_p & 0 & 0 & 0 \\ 0 & R_q & 0 & 0 \\ 0 & 0 & R_2 & 0 \\ 0 & 0 & 0 & R_3 \end{bmatrix} \tag{2}$$

$$\boldsymbol{L} = \begin{bmatrix} L_p & M_{pq} & M_{p2} & M_{p3} \\ M_{pq} & L_q & M_{q2} & M_{q3} \\ M_{2p} & M_{2q} & L_2 & M_{23} \\ M_{3p} & M_{3q} & M_{32} & L_3 \end{bmatrix} \tag{3}$$

where $R_p = (N_p/(N_p + N_q))R_1$, $R_q = (N_q/(N_p + N_q))R_1$ and N_p, N_q are the number of turns of the subcoil p and q.

Since the self-inductance of a coil is proportional to the number of turn squares in the low-frequency range, we further get the following relation of L_p and L_q:

$$\frac{L_p}{L_q} = \left(\frac{N_p}{N_q}\right)^2 = k^2. \tag{4}$$

From the consistency property [7], we can obtain that:

$$L_1 = L_p + 2M_{pq} + L_q \tag{5}$$

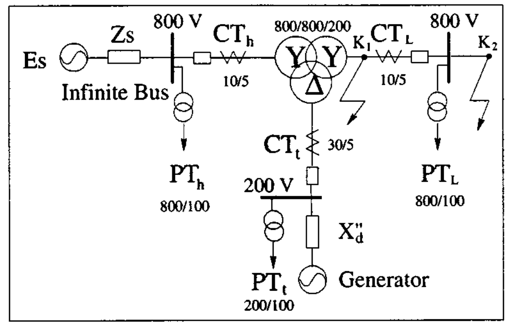

Fig. 1. Reduced equivalent diagram of the EPDL system.

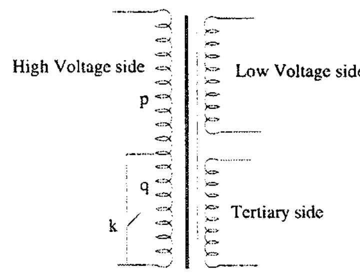

Fig. 2. Turn-to-ground fault.

$$M_{12} = M_{p2} + M_{q2} \tag{6}$$

$$M_{13} = M_{p3} + M_{q3}. \tag{7}$$

At first, let the low voltage and tertiary side be open to simplify this solution. However a circulating current i_Δ exists in the Δ windings even though the terminal current $i_3 = 0$. This current i_Δ can be solved from the differential equation of the unfaulted phase.

Now apply a turn-to-ground fault on the high voltage side. The following differential equations can be derived:

$$R_p i_1 + L_p \frac{di_1}{dt} + M_{pq} \frac{di_q}{dt} + M_{p3} \frac{di_\Delta}{dt} = v_1 \tag{8}$$

$$R_q i_q + L_q \frac{di_q}{dt} + M_{pq} \frac{di_1}{dt} + M_{q3} \frac{di_\Delta}{dt} = 0 \tag{9}$$

$$M_{p2} \frac{di_1}{dt} + M_{q2} \frac{di_q}{dt} + M_{23} \frac{di_\Delta}{dt} = v_2 \tag{10}$$

$$R_3 i_\Delta + L_3 \frac{di_\Delta}{dt} + M_{p3} \frac{di_1}{dt} + M_{q3} \frac{di_q}{dt} = v_3. \tag{11}$$

There are eight unknowns: L_p, L_q, M_{pq}, M_{p2}, M_{q2}, M_{p3}, M_{q3}, i_q, and we have six measurements: i_1, v_1, i_2, v_2, i_3, v_3, plus two known resistance R_p, R_q. All the eight unknowns can be solved from these nonlinear differential equations. At first we assume:

$$M_{pq} = \sqrt{L_p L_q} = kL_q. \tag{12}$$

That is the leakage factor $\sigma = 1 - (M_{pq}^2/L_pL_q)$ is set to zero first. From (4), (5), and (12), we can obtain:

$$L_q = \frac{L_1}{(1+k)^2} \qquad L_p = k^2 L_q.$$

Add (8) and (9) to solve i_q by using the trapezoid rule. After i_q is solved, M_{p1} can be estimated from (9) by the least error squares estimation technique. Then one can find the optimal estimation of M_{pq} by selecting:

$$M_{pq}^{\text{opt}} = \min_{0\le\sigma\le 1} \sum_{t=t_{\text{fault}}}^{t_{\text{end}}} \left[R_q i_q + L_q \frac{di_q}{dt} + M_{pq}\frac{di_\Delta}{dt} + M_{q1}\frac{di_1}{dt}\right]^2 \quad (13)$$

where, t_{fault} is the beginning time of the fault, and t_{end} is the end time of the fault. After optimal M_{pq}^{opt} is solved, the self-inductance of subcoil p and q can be solved from (4) and (5). Accordingly we can solve M_{ip}^{opt} and $M_{iq}^{\text{opt}}(i = 2, 3)$ from (10) and (11).

In the above procedure, the high voltage side is taken as an example to illustrate how to estimate the parameters for the model of the transformer winding fault. Actually for faults at other sides and the $Y/Y/Y$ or $Y/\Delta/\Delta$ configuration, a similar estimation procedure can be performed to obtain all the elements of the RL matrix.

B. The Turn-to-Turn Fault Mode

After the parameters of the turn-to-ground configuration are estimated, we can do this estimation again to get the other group of parameters for the turn-to-ground configuration. From these two groups of RL parameters, the turn-to-turn fault shown in Fig. 3 can be modeled by two 5 × 5 $\boldsymbol{R}$ and $\boldsymbol{L}$ matrices.

Reference [7] gives the detail derivation for building these two 5 × 5 $\boldsymbol{R}$ and $\boldsymbol{L}$ matrices based on the two turn-to-ground fault 4 × 4 $\boldsymbol{R}$ and $\boldsymbol{L}$ matrices, and it is not repeated here again.

The proposed estimation method is verified first by a power transformer model presented in [8]. The leakage factor σ is specified as 0.40 and 0.0015 (the one from [7]). The summation voltage $S(M_{pq})$ is calculated from the range $\sigma = 0$–1.0, and plotted in Fig. 4.

From this figure, it can be found that the estimated leakage factor (0.401) based on a coupling RL transformer model is very close to the specified value (0.40) for the case 1. The estimate of the leakage factor converges monotonously from both sides for these two cases. This feature assures that one can finally get the real leakage factor from any initial leakage factor. For the case 2, the optimal leakage factor is exactly the specified value 0.0015.

More cases have been simulated by changing the fault location and leakage factor. From the simulation results, it is found that this estimation method is very accurate. They all converge to the specified leakage factor from both sides. After the optimal leakage factor is estimated, the further estimation for other parameters is exactly as expected.

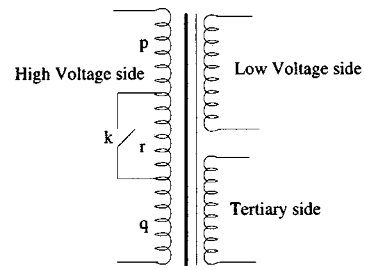

Fig. 3. Turn-to-turn fault.

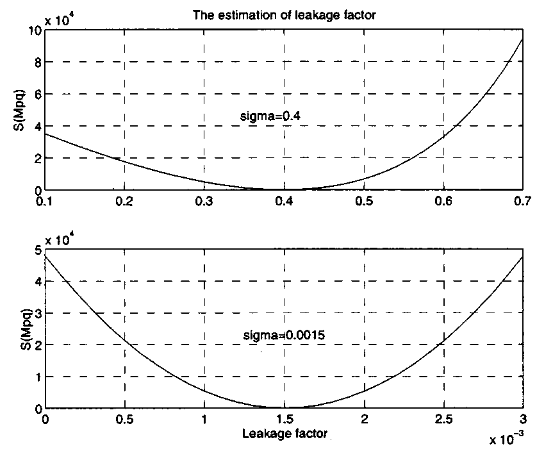

Fig. 4. Summation voltage versus leakage factor.

C. Modeling of the Sound Winding

The coupled RL branch model is applicable for turn-to-turn fault simulation of a power transformer, but not for the modeling of the nonlinear magnetic coil. This study is very much interested in how a large inrush current impacts the performance of the digital relay. In EMTP/ATP, type-96 nonlinear reactor model has the ability to model the residual flux which is a very important variable in determining the inrush current.

The configuration of the model used in this study is shown in Fig. 5. In this model, the saturated nonlinear inductance is replaced by type-96 element, and it is moved to the transformer terminal parallel with the magnetizing resistor R_m.

IV. Modeling of the Power Transformer Protection System

How to accurately model the relay has paramount importance in the relay performance evaluation. Since WBZ-500 was developed by one of the authors in EPDL at HUST, this relay is chosen in the relay performance evaluation study. Both the hardware and software of this relay modeled in MATLAB will be discussed in this section [9]. It should be pointed out that the digital relay modeling technique in this paper can also be used for modeling of other digital relays.

A. Hardware Modeling of WBZ-500 System

Three microprocessors (V40 CPU, compatible with Intel 80 186) perform the protection scheme individually. Two of them implement the differential protection, and the other one is for the back up protection.

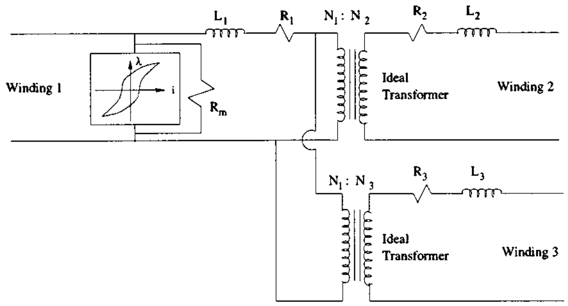

Fig. 5. Transformer sound winding model.

1) Isolation (Auxiliary) Transformers: The auxiliary transformers are used to provide electrical isolation of the input circuit. The voltage transformers provide low voltage suitable for the electronic components of the relay. The current transformers are employed to drive resistive burdens to generate proportional voltages. In this study, the auxiliary transformers have been modeled as being linear, and this may limit the validity of the results in some cases.

2) Anti-Aliasing Filter: In WBZ-500 system, the sampling rate is 16 points a cycle. The sampling frequency is 16 × 50 Hz = 800 Hz. It is necessary to design a filter in which the –20 dB frequency is less than the Nyquist frequency (400 Hz). An active anti-aliasing filter is used in the WBZ-500 system design. The schematic circuit is shown in Fig. 6. The first stage is a voltage divider which is used to match the discrepancy of the CT's and the power transformer turn ratios.

Simulation program with integrated circuit emphasis (SPICE) is a powerful, general-purpose circuit analysis program that simulates analog circuits. It can be used to study the analog circuits behavior with high accuracy [10].

After the SPICE simulation is performed, it is found that the difference between the SPICE result and the one using the ideal operational amplifier is negligible in the frequency range 0–10 000 Hz. This large frequency interval is good enough for the digital protection application. The transfer function $H(s)$ is obtained after the ideal operational amplifier is used. After mapping the s plane into z plane by the bilinear transformation, two vectors a and b are obtained from the transfer function $H(z)$:

$$H(z) = \frac{B(z)}{A(z)} = \frac{b_1 + b_2 z^{-1} + \cdots + b_7 z^{-6}}{1 + a_2 z^{-1} + a_3 z^{-2} + \cdots + a_7 z^{-6}}. \quad (14)$$

MATLAB provides a function, *filter*, to implement the above digital filter, and its frequency response characteristic is consistent with the SPICE simulation result.

3) Analog-to-Digital Conversion: In a computer simulation, the signal source data is in a discrete form, and all the signal samples are synchronized. This scheme is used in the WBZ-500 relay A/D conversion board. In this study, the time step of ENITP/ATP simulation is set to 0.25 ms, one fifth of the WBZ-500 system sampling period. This time step specification of the EMTP/ATP simulation makes the modeling of A/D conversion very simple: The input signal to WBZ-500 system is extracted from the output waveform of the anti-aliasing filter every five points. The input samples are not converted to an integer number, but directly fed to the protection algorithm.

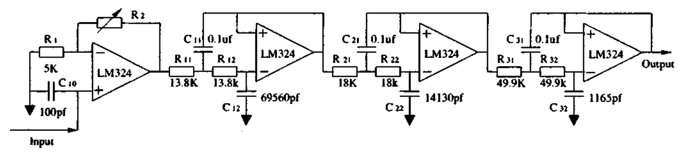

Fig. 6. Anti-aliasing filter schematic circuit.

The effect of the conversion time should be considered in the trip time module of the computer simulation.

B. Software Modeling of WBZ-500 System

In this paper, we focus on the study of the current differential protection, the primary protection of a power transformer. The protection schemes adopted in these two primary protection relays comprise of two major parts discussed below.

1) Percentage Differential Protection: Three straight lines form the trip boundary to discriminate the external fault from the internal fault for both of the two primary relays. The 16 points discrete Fourier algorithm is used to calculate the fundamental, second and fifth harmonic components. The square root function is not available in the Intel 80 186 CPU instruction set. An approximation method is used in WBZ-500 to estimate the square root with acceptable accuracy (its maximum related error is less than 0.17%):

$$Y^F = \sqrt{Y_s^{F^2} + Y_c^{F^2}} \approx L + \frac{5S^2}{3(3L+S)} \quad (15)$$

where, $L = \max(|Y_s^F|, |Y_c^F|)$, $S = \min(|Y_s^F|, |Y_c^F|)$, and Y_s^F, Y_c^F are sine and cosine parts of the Fourier algorithm. In the modeling of WBZ-500 system, this approximation method will be adopted in order to closely model the algorithm used by the protection relay.

2) Inrush and Overexcitation Restraint Protection: It consists of the following functions:

- Harmonic restraint function for the primary protection 1. Two criteria are checked:
  1) the second harmonic for inrush current restraint;
  2) the fifth harmonic for overexcitation restraint.
- Mixed restraint function for the primary protection 2: the voltage restraint function plus volts-per-hertz protection are adopted:
  1) Voltage restraint function for fast inrush current identification:

$$V \begin{cases} \le V_t & \text{trip circuit breakers} \\ > V_t & \text{go to second harmonic protection} \end{cases} \quad (16)$$

  where V is the magnitude of the faulted phase voltage, V_t is the threshold.

  2) Volts-per-hertz protection for overexcitation:

$$\frac{V^*}{F^*} \begin{cases} \le UF_{set} & \text{trip circuit breakers} \\ > UF_{set} & \text{overexcitation} \end{cases} \quad (17)$$

  where V^* and F^* are per unit voltage and frequency of the power system. UF_{set} is the setting value for overexcitation restraint, and usually it is set to 1.10.

The two primary protection schemes are modeled by using MATLAB [9].

V. Verification of Transformer Fault Simulation and Demonstration of its use in the Relay Evaluation

The modeling of the power transformer in EPDL is verified first by comparing ATP simulation result an digital fault recoder (DFR) data. The interaction between the ATP program and relay model is also demonstrated during the simulation. Finally WBZ-500 differential protection is evaluated by the ATP transient waveform. This provides a good example of how the computer simulation benefits the performance evaluation of a digital relay.

A. Transient Verification for the ATP Representation of the EPDL Power System Model

1) The Simulation of the Transformer Winding Fault: The turn-to-ground and turn-to-turn faults were applied in the high voltage side of the power transformer to verify the modeling technique proposed in this paper. The fault location shown in Fig. 3 is defined by:

$$\frac{N_{r+q}}{N_{p+r+q}} = 60.7\% \qquad \frac{N_q}{N_{p+r+q}} = 39.3\%$$

where N stands for the number of winding turns, and the subscript represents the subcoil of the winding.

At first, two turn-to-ground faults are conducted between $r+q$ and q in phase A of the high voltage side. Both the low-voltage and tertiary side are open circuits. The transient waveform is recorded by DFR and used to estimate the leakage factor. The estimation result is that $\sigma = 0.0012$ for $r+q$ short circuit fault, and 0.0011 for the subcoil q short circuit fault. This flat feature is also observed in [7]. The ATP model for the turn-to-turn fault study is then established from these two tests.

Finally the subcoil r is shorted for the study of the turn-to-turn fault. The ATP simulation results and DFR waveforms are plotted in Fig. 7. From this figure, it can be observed that the current waveform of ATP simulation matches the DFR recordings very well. A little difference exists in the faulted phase voltage magnitude. The other two unfaulted phase voltage waveforms match very well.

This verification demonstrates that the splitting RL coupling network is a simple and valid ATP model for the turn-to-turn fault transient study. The flat feature of the leakage factor σ, which is about 0.0012 in this transformer, will be extended to the small turns winding fault.

2) The Simulation of the Transformer Inrush Current: After the system configuration is given, two groups of parameters will determine the inrush current: fault inception angle and residual flux. The inception angle can be obtained from the DFR data. However for residual flux, it is very difficult to get it from the DFR data [11]. In this ATP simulation, all the three phase transformer residual fluxes are coordinated to let the ATP simulation result approach the DFR data. Because of the Δ configuration in the tertiary side, any change for one phase residual flux will affect all the three phase inrush currents. This property makes the setting of the residual flux very complicated. One set of the ATP simulation result is shown in Fig. 8.

It is noted that the magnitude of the ATP simulation inrush current is close to the DFR data for phases B and C, especially

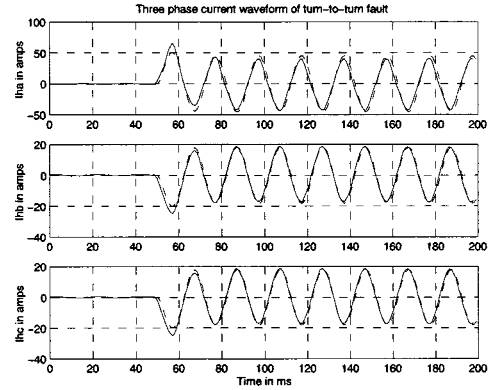

Fig. 7. The comparison of ATP simulation and DFR result for turn-to-turn fault (dashed line—ATP, solid line—DFR).

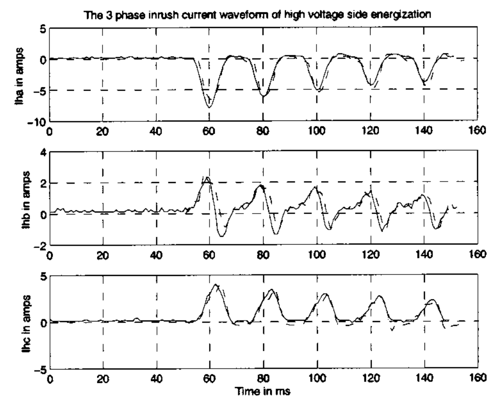

Fig. 8. The comparison of ATP simulation and DFR data for inrush current (dashed line—ATP, solid line—DFR).

the decaying rate is almost the same. For phase A, the decaying rate in the ATP simulation is a little slower than the DFR data. A better ATP simulation result may be achieved after more combinations are tested.

Theoretical analysis shows that the maximum possible inrush current occurs when the transformer is energized at zero voltage (with voltage increasing in the positive direction) and a positive maximum residual flux (70% of the peak residual flux in our case). The conclusion is verified for a single phase power transformer. It is observed that the peak value of the inrush current reached 20 A in the first crest. Any deviation from either the inception angle or the residual flux will reduce this peak value. This operating condition for the maximum inrush current will be used in the following relay performance evaluation.

B. Use of the Transformer Fault Simulation in Evaluating WBZ-500 Differential Protection

Since the transient waveform is available, it can be used to evaluate the performance of different relay algorithms, check the feasibility of different protection schemes, optimize the setting of the relay for a specified system, etc. This section focuses on the evaluation of WBZ-500 differential protection. The simulation for the turn-to-turn fault involving inrush current is used as an example to demonstrate the benefit of the computer simulation.

This fault occurs when a turn-to-turn fault has existed in the transformer winding before the transformer energization. This case is one of the most challenging for the differential protection design. It will determine how sensitive the relay can be in detecting the turn-to-turn fault, and how fast the relay can correctly detect this fault. Because of the physical limitation of the transformer structure in EPDL, eight is the smallest number of turns for the turn-to-turn fault that can be considered. The number of turns of the whole winding is $N_{p+r+q} = 466$ turns. Eight turns is about 1.7% of the whole winding.

Combining the turn-to-turn winding model in phase C with other two sound phase transformer models allows one to form a three phase transformer model and evaluate the performance of WBZ-500 for such a special case. The condition of maximum possible inrush current in phase A is set to observe the performance of WBZ-500 for the turn-to-turn fault. The maximum negative residual flux is specified to be in phase B. The two primary relays are evaluated under this rare condition. The simulation result shows that the possible maximum inrush current may slow down the trip speed. The major cause for this delay comes from the coupling of the sound phase inrush current. In the faulted phase, the transformer is unsaturated, and there is no inrush current generated except the components coming from the coupling of the tertiary side. This trip delay was also observed in the differential protection study on another power transformer in EPDL [12].

The differential current for this 1.7% turn-to-turn fault was 2.0 A (secondary value) in EPDL testing. This value is largely affected by the fault resistance. If no fault resistance and inductance are introduced in the short circuit, a numerical problem will cause the ATP simulation to diverge. A small inductance value (0.001 Ω) is used here to prevent such divergence. Comparing with the impedance of self-inductance of the subcoil r (1.24 Ω) this artificial inductance is very small. However the resistance of the subcoil r is 0.0069 Ω. Obviously the impact of the contact resistance to conduct this turn-to-turn fault in EPDL can not be ignored. The steady state differential current will be used as a reference to determine the contact resistance. When the fault resistance is set to 0.02 Ω, the calculated differential current in WBZ-500 simulation program is 1.978 A. This is very close to the recorded WBZ-500 testing result of 2.0 A. In the following tests, 0.02 Ω is used as the fault resistance default.

The WBZ-500 system can successfully detect the eight turns short circuit fault, although the trip delay is observed in some cases. Because of the physical limitation of the winding structure, there is no way to investigate the performance of WBZ-500 for smaller turns short circuit in EPDL, such as four. Computer simulation, however, can provide a tool to do this sensitivity study.

The setting of I_{d1} will largely determine how many short circuit turns the relay can detect under the specified system operation conditions, such as source impedance, the magnitude and phase angle of the power source, etc. In this study, I_{d1} is set to 1.0 A.

Reducing the number of short turns to four, the fault resistance and inductance are set to be the same as in the above case. After the computer simulation, it is found that the relay can not operate for this fault. The fault phase current is about 0.65 A in the steady state. Even after the inrush current has decayed to the steady state excitation current, the WBZ-500 system can not operate for this small fault current.

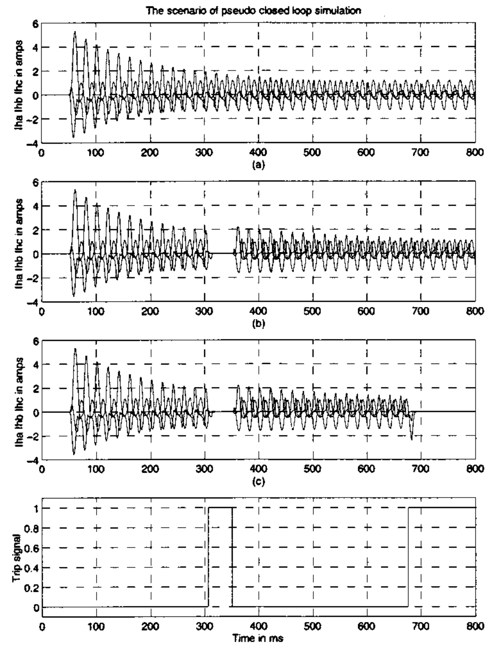

Fig. 9. The operation of WBZ-500 for inrush current with 4 turns short circuit fault.

If the fault resistance is reduced from 0.02 to 0.01 Ω, the WBZ-500 system can successfully detect this fault with a significant delay in operation as shown in Fig. 9.

Fig. 9(a) is the original ATP waveform of the high voltage side three phase currents. Fig. 9(b) combined with the trip signal at the bottom of this figure reflects the response of WBZ-500 system, where the 1 stands for trip signal, and 0 for the no operation. Since the reclosing scheme is adopted, the new transient waveform is shown in Fig. 9(b). Because the fault still exists, the fault current shows up again after the circuit breakers are reclosed. The WBZ-500 relay will continue to process the new transient waveform beginning with the reclosing moment. This relay issues the trip signal again for the existing internal fault. This sequence is achieved by running ATP three times according to the relay response. Any circuit operation will change the power system network. This operation is reflected after rerunning the ATP program. The modification of the switch card in ATP program due to circuit breaker operation is achieved by a program written in C.

The first energization condition is the same as the above case, and the maximum inrush current occurs in phase A. Surprisingly the trip delay after reclosing with small inrush current is longer than the first energization with large inrush current. The coupling current from the tertiary side makes the prediction of the trip time very difficult.

The expected longer trip delay for turn-to-turn fault involving the inrush current was hard to capture in the EPDL evaluation for WBZ-500 system. The computer simulation allows us to see how the fault condition affects the performance of WBZ-500 system. The above examples illustrate the ability of computer simulation to evaluate the performance of WBZ-500 system under different operation conditions which may not be possible to conduct in the real power system the protection may serve, or even in the analog power system laboratory evaluation.

VI. Conclusion

- An EMTP/ATP model of a power transformer is established and verified by using test data. A new way of modeling transformer faults is introduced, while accurately representing other transformer operating conditions (such as inrush) as well.
- This power transformer modeling technique can be used in representing power transformer transients, which is very important in testing and evaluating protective relays. It allows generation of some difficult fault cases for the power transformer protection performance evaluation that may not be possible using any other known physical means.
- The special case using a commercial digital power transformer relay (WBZ-500) modeled by MATLAB demonstrates the ability and benefit of the computer simulation in evaluating performance of the power transformer protection.

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