EXPERIMENTAL EVALUATON OF EMTP-BASED CURRENT TRANSFORMER MODELS FOR PROTECTIVE RELAY TRANSIENT STUDY

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Abstract– This paper describes an EPRI study of Current Transformer (CT) digital models intended for protective relay transient performance analysis. Experimental evaluation of CT models implemented using Electro Magnetic Transient Program (EMTP) was carried out.

Two relaying CTs with 600/5 and 2000/5 ratios were used in the study. Experiments in a high power laboratory were performed to obtain transient responses. Simulation of the CT response to the same transient events was set up using three different CT models. They were implemented based on the saturable transformer and nonlinear reactor models available in an EMTP.

Comparison of laboratory and simulation results indicates that CT models developed based on the EMTP program give satisfactory results for most of the cases. It has also been discovered that in some instances EMTP models need further improvements.

Keywords: Current Transformer, Transient Response, Digital Simulation, EMTP.

I. INTRODUCTION

In the recent EPRI development of a digital simulator for protective relay testing, a need for digital modeling of instrument transformers was identified [1,2]. Transient behavior during fault events has been of a particular interest [3].

The steady state performance of current transformers (CT) is fairly well understood [4]. However, the transient performance is not specified by any standard. A number of studies have been conducted to investigate phenomena of CT transient behavior.

Various analytic approaches to the analysis of CT transient responses have been presented in the past [5-9]. Comparison between responses of some of the models published in the literature and the experimental results were also discussed [10]. A hysteresis modeling used in the EMTP program was analyzed in detail [11]. Several papers were written concentrating on the influence of hysteresis on a CT transient response [12,13].

The mentioned studies gave considerable insight into CT transient behavior as well as some understanding of the influence of this behavior on protective relaying performance. However, the published results did not indicate how a digital CT model could be developed, based on the readily available measurements and information provided by the manufacturers, to provide accurate transient behavior and yet to be easily interfaced to a network transient simulation program. The EMTP approach for CT modeling seems to be an ideal choice but there was no comprehensive data published regarding evaluation of the digital models of CTs implemented using EMTP modeling facilities.

This paper gives results from an experimental study aimed at evaluating digital models of current transformers implemented based on the EMTP modeling techniques [14].

Transient response tests were performed on CTs in a high power laboratory and the results have been compared with digital simulations of the same events carried out using EMTP-based CT models. The model implementation approaches are discussed first. Description of the high power laboratory test and EMTP simulations are given next. The comparison results and conclusions are given at the end.

II. MODEL IMPLEMENTATION

The input signal for most of protective relaying is obtained from current transformers for current input and from potential transformers or coupling capacitor voltage transformers for voltage input. The connections for line protection are shown in Figure 1.

CT models presented in this paper are developed based on the EMTP features [15]. The models are built as ready to use modules that can easily be included in a power system model developed using EMTP. The line where CT models are to be incorporated must be cut producing two nodes as shown in Figure 2. The nodes are to be named as CTIxxx and CTOxxx, where xxx is a CT number. The relay is connected between the CT model node CTSxxx and ground. To include CT model file in the main power system model file, statement ($INCLUDE filename) may be used.

The CT models presented in this paper are built for bushing type CTs. The CT data, which includes the V-I characteristics and the secondary winding resistance, is either available from the manufacturer or can easily be measured.

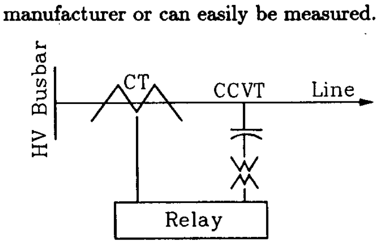

Fig. 1. Instrument Transformer Connections in a Power System

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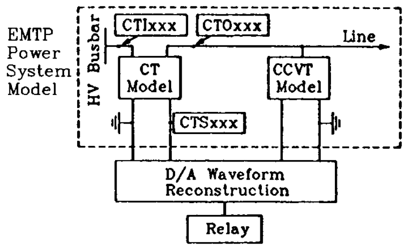


Fig. 2. CT model included in a Power System Model

A model for a single phase power transformer with core saturation exists in EMTP. This model comprises of an equivalent circuit built around an ideal transformer as shown in Figure 3(a). The magnetization branch is represented internally as a nonlinear inductor whose $\lambda - i$ characteristics is specified in piecewise linear form by the user. Since the $\lambda - i$ characteristics is usually not readily available, EMTP provides an auxiliary routine to convert the more commonly used $V_{rms} - I_{rms}$ characteristics into an equivalent $\lambda - i$ set. This transformer model can be used to represent a CT.

An equivalent way of modeling the CT is by explicit use of the Type-98 nonlinear inductor model available in EMTP together with the above described saturable transformer model. In this case, the magnetizing branch is purposely made dormant (i.e. no saturation is modeled) in the EMTP saturable transformer model of Figure 3(a) while choosing artificially small (e.g. 1.0 e-6) values for the secondary resistance and leakage inductance. The Type-98 nonlinear inductor model can then be connected at the secondary terminals of this simplified transformer and the actual secondary leakage impedance (R_s, L_s) can be attached to the secondary terminals as shown in Figure 3(b). The resulting model of Figure 3(b) with the Type-98 element and that of Figure 3(a) are identical. However, the input data for the saturation characteristics will be referred to different sides of the ideal transformer in the two models. Since the V–I characteristics are available for the secondary side of a CT, the CT model is implemented according to Figure 3(b) in this study.

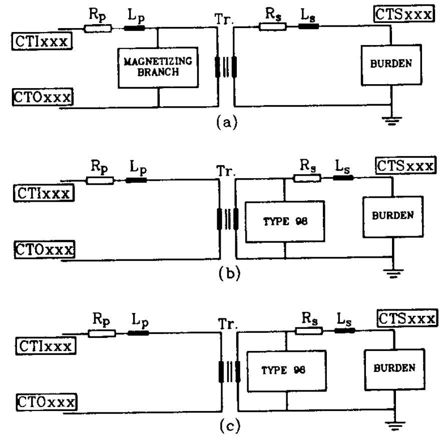
Since the saturation effects are modeled using the single valued nonlinear inductor model (Type-98) of EMTP, this transformer model can not account for the hysteresis effects in the transformer core.

The hysteresis effects can explicitly be modeled using another EMTP component referred to as Type-96 nonlinear element in the EMTP manual [15]. A support routine exists in EMTP for obtaining hysteresis characteristics from the known V–I curve. The saturation point on the curve needs to be determined in order to use this routine. Thus, a CT model which accounts not only for saturation but also for the hysteresis can be built by simply replacing the Type-98 element model with the Type-96 element model as shown in Figure 3(c).

III. TESTS AT A HIGH POWER LABORATORY

This section outlines tests performed on the actual CTs at a high power laboratory.

Two bushing type CTs with core material ARAMCO 4 were selected for the tests. CT data is given in Table I.



Rp–primary winding resistance
Lp–primary winding leakage inductance
Rs–secondary winding resistance
Ls–secondary winding leakage inductance
Tr–ideal transformer

Fig. 3. EMTP–based CT Models: (a) CT Model #1, (b) CT Model #2, (c) CT Model #3

Table I. Current Transformer Data

CT	1	2
Ratio:	600/5	2000/5
Accuracy Class:	C400	C800
Burden (VA):	100	200

Measurement of the V–I curve was carried out according to the ANSI/IEEE standard C57.13/1978 [4]. The results are shown in Figure 4.

CT leakage inductance was not measured since its value is small comparing to CT rated burden and its influence on CT transient response in this case can be neglected. This was confirmed in discussion with the CT manufacturer. In the following study, CT leakage reactance is assumed to have a value of 0.5Ω at 60 Hz.

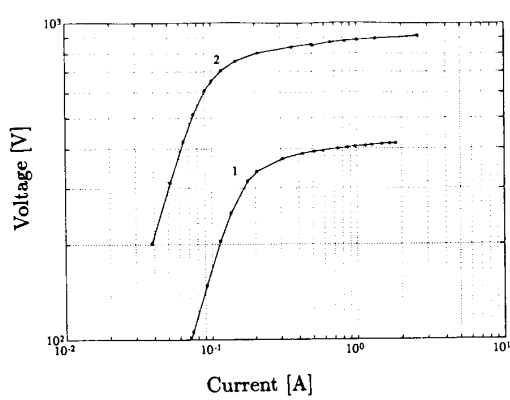


Fig. 4. Current Transformer V–I Characteristics; 1 - CT 600/5; 2 - CT 2000/5.

Measurement of the secondary winding resistance was performed by using a multimeter. Resistances of 0.34Ω and 0.72Ω were obtained for 600/5 and 2000/5 CTs respectively.

The high power test circuit is given in Figure 5. The test description is given in Table II. Primary and secondary currents, secondary voltage, and flux density were measured. In order to measure flux density, two additional winding were wound on the tested CTs. CT remanence was implemented by applying DC current. DC implementation was done to obtain maximum remanence. Value of DC currents are also shown in Table II. Test waveforms for each of the test cases are shown in the corresponding Figures indicated in Table II.

Table II. CT Test Conditions

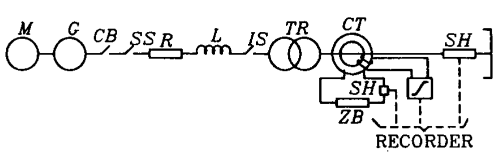
Test #	CT	Burden [Ω]	$I_{sym}[A_{rms}]$	Remanence	Fig. #.
1	600/5	2+j 3.5	4450	No	13
2	2000/5	4+j 7	12690	No	14
3	600/5	4	5120	No	15
4	2000/5	8	12050	No	16
5	2000/5	8	8380	Yes $I_{dc} = 2.16A$	17
6	2000/5	8	7670	Yes, Reverse $I_{dc} = 2.4A$	18

IV. EMTP SIMULATIONS

The three CT models, which are built to simulate protective relay transients, are comparatively evaluated. The evaluation is carried out by comparing the measured transient response obtained in a high power laboratory with the EMTP simulations of the same events.

The test circuit diagram used for EMTP simulations is given in Figure 6. Circuit parameters R_l and L_l are selected to produce the same X/R ratio as it was in the high power laboratory. The incidence angle may be controled by the switch SW2.

The next step was to implement the EMTP-based CT models. This requires utilization of hysteresis and V-I curves. Approach taken in this paper for hysteresis and V-I curve generation is presented below.



M–1750 Hp Drive Motor
G–Short Circuit Alternator
CB–Circuit Breaker
SS–Synchronized Make Switch
R–Variable Resistor
L–Variable Reactor
IS–Isolation Switch
TR–Test Transformer
CT–Tested CT
Zb–CT Burden
SH–Shunt

Fig. 5. CT Short Circuit Test Setup at the High Power Laboratory

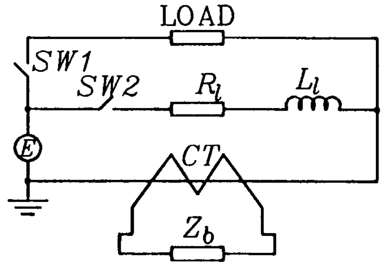


Fig. 6. Circuit Diagram Used in EMTP Simulation of the CT Laboratory Tests

The hysteresis loop in EMTP can be specified either by providing data points directly or by calculating data points from V–I curves.

The first approach requires measurements from an actual CT. There are two possible methods for measurements. One is measurement of the steady state hysteresis. This can be done in laboratory under 60 Hz excitation by driving the CT into deep saturation. The other method is to use direct hysteresis measurements obtained during transient testing of a CT.

The second approach is to generate hysteresis using the EMTP auxiliary program HYSDAT and the manufacturer's V-I curve for the core. This approach is convenient since a typical relay engineer will have access to this kind of data rather than the laboratory measurements. HYSDAT automatically generates hysteresis once V–I curve data are provided. The shape of the hysteresis generated this way is a function of the core material as well as the construction geometry. The EMTP currently supports only one type of material (ARMCO M4 oriented steel) in representing the core, and therefore the user is only to specify the saturation point (flux–current) in order for the EMTP to rescale the assumed hysteresis.

It is found that the choice of the saturation point can greatly affect the resulting hysteresis generated by EMTP and consequently the transient simulations. In order to evaluate this problem in more detail, the following steps were performed:

- 600/5 A CT steady state hysteresis was measured experimentally.
- The experimental data have been directly included in the EMTP type 96 element. Steady state hysteresis was then generated by simulation.
- Two saturation points were selected on the V–I curve as shown in Figure 7. Two different hysteresis using these two points were generated using EMTP auxiliary programs.
- Comparison between the measured hysteresis and the two obtained using different saturation points on the V–I curves is performed as given in Figure 8.
- Two cases of comparative CT transient responses were considered as given in Figure 9 and 10.
- Figure 9 gives CT transient response obtained experimentally versus responses obtained through EMTP simulations for two different saturation points on the V–I curve.

- Figure 10 gives the CT transient response obtained by directly using the hysteresis generated by an EMTP type 96 element incorporating the experimental data. This response is compared to the response obtained by EMTP simulation for saturation point #2 on the V–I curve, and the experimentally obtained CT response.

The results shown in the Figures 8–10, indeed, demonstrate the influence of the saturation point selection on both the hysteresis loop generation and CT transient response. It is also demonstrated that an appropriate procedure has to be defined in order to obtain accurate simulation of hysteresis and CT responses. This procedure can be developed by making appropriate adjustments in the EMTP source code. Since the authors did not have access to the EMTP source code, only the "external" corrections were made. These are described in the following text.

The problem of the appropriate V–I curve slope simulation in the saturated region and the problem of flux–current curve generation is discussed next.

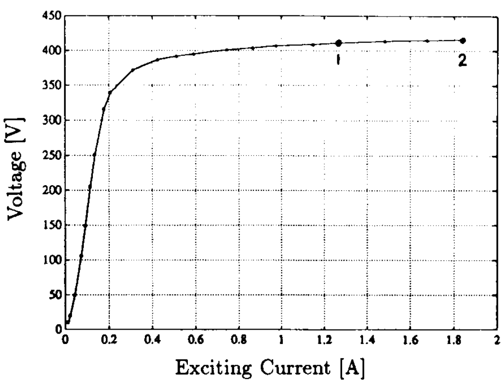
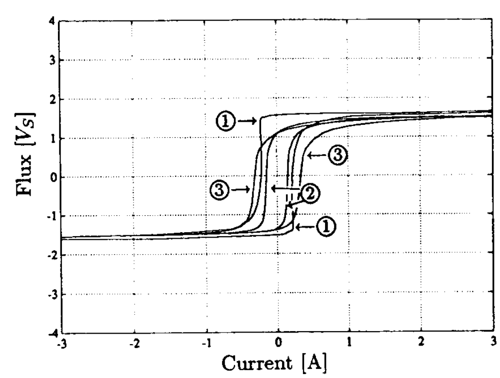
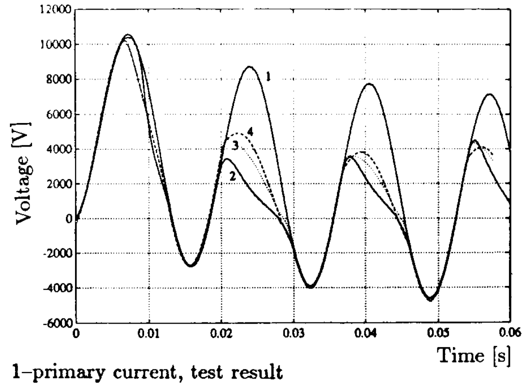


Fig. 7. Selection of the Saturation Point for Calculation of Hysteresis



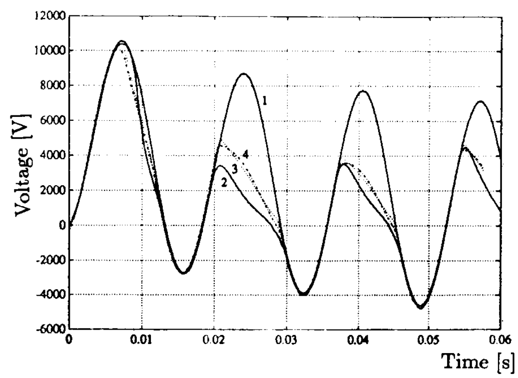
1 - hysteresis obtained by measurement
2 - EMTP generated hysteresis loop for point 1 from Fig. 7
3 - EMTP generated hysteresis loop for point 2 from Fig. 7

Fig. 8. Comparison among the Hysteresis obtained by Measurement and the Ones Generated by EMTP for the Two Selected Points from Fig. 7



1–primary current, test result
2–secondary current, test result
3–secondary current for the hysteresis using point 2 on Fig. 7
4–secondary current for the hysteresis using point 1 on Fig. 7

Fig. 9. CT Secondary Currents for the Two Different Hysteresis



1–primary current, test result
2–secondary current, test result
3–secondary current for the hysteresis generated by EMTP using point 2 on Fig. 7
4–secondary current for the hysteresis obtained by including experimental data in the Type 96 element

Fig. 10. CT Response for the Hysteresis Based on Experimental Results and the One Obtained by using the EMTP

Note: In all figures showing CT responses, secondary currents are referred to primary

As mentioned earlier, the V–I curve is not directly used in the EMTP simulations. EMTP provides an auxiliary routine to convert the V–I curve into an equivalent flux–current data set. This data set is then used by EMTP. The EMTP auxiliary routine generates and extends the V–I curve with the same slope as the slope between points $n-1$ and n of the input data.

If V–I curve data breakpoints are not monotone increasing (contain "noise"), then the generated flux–current curve may be extended with the high slope, as shown in Figure 11. That may have significant influence on the CT transient response simulation.

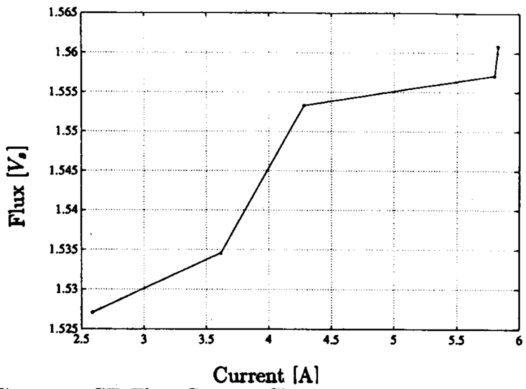


Fig. 11. CT Flux–Current Characteristic Representing the Noise (only the last four segments from Fig. 4 for 600/5A CT are shown)

The problem may be solved by arbitrarily obtaining the flux–current curve with the very small slope in the saturated region. This method is achieved by adding a large number for the highest current point data input, and leaving the value for flux unchanged. This will result in EMTP extending flux–current curve with a very small slope. In this study, value of one was added in front of the highest current point data.

The same problem is present when hysteresis is generated since the flux–current curve is used for this purpose. Hysteresis is generated based on a selected saturation point from flux–current curve. EMTP auxiliary routine then automatically generates hysteresis. In order to obtain the hysteresis for deep saturation, the flux–current curve has to be extended as described earlier.

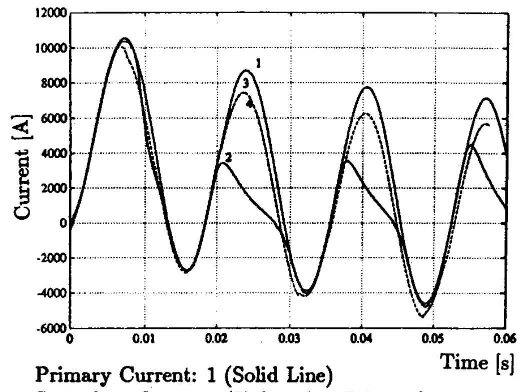
The EMTP simulations illustrating effects of these corrections are shown in Figure 12 for 600/5 CT. Figure 12a represents CT response for the CT Model #1 and #2 with the "noisy" V–I curve input data. The CT Model fails to represent the actual, distorted secondary current. When the correction is performed, as shown in Figure 13 (Curve #3), the CT response is closer to the experimenatlly obtained one. Figure 12b represents CT response for the CT Model #3 for the case where the hysteresis was generated with and without correction. The influence of the correction is evident.

All the simulations performed for validation purposes were performed using the V–I curve with the slope in the saturated region corrected as described in the following section.

V. MODEL VALIDATION

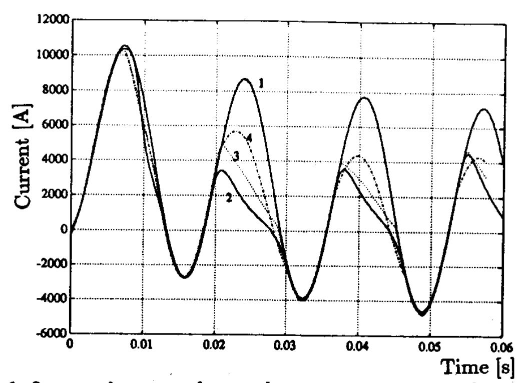
In order to create the identical operating conditions as the ones during actual measurements, the laboratory test parameters such as primary circuit time constant, symmetric test current amplitude and the incidence angle have to be determined. These parameters are calculated from the test waveforms using a program, specially developed for this purpose.

As mentioned earlier, two different CTs, namely CT 600/5 and CT 2000/5, are tested under six different operating conditions. These test cases are summarized in Table II.



Primary Current: 1 (Solid Line)
Secondary Currents (Referred to Primary):
Test Result – 2 (Solid Line)
CT Model #1 – 3 (Dashed Line)
CT Model #2 – 4 (Dotted Line)
Test Parameters: $I_{symmetric} = 4425 A_{rms}$; $(2 + j3.5)\Omega$;
No Remanence

Fig. 12a. EMTP CT Transient Response Simulation Using V–I Characteristic Without Correction



1, 2 – primary and secondary currents, test result
3 – CT model response using hysteresis with correction
4 – CT model response using hysteresis without correction

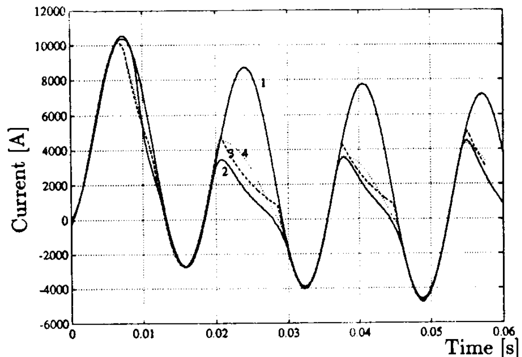
Fig. 12b. EMTP CT Transient Response Simulation Using the Hysteresis With and Without Correction (CT Model #3)

Figures 13–18 show the results of the actual measurements, and the EMTP simulations for the six test cases described in Table II. The following is a discussion of the results.

As described at the beginning of Section 2, CT models #1 and #2 use the same non–linear element Type 98 to represent magenetizing branch. As a result CT models #1 and #2 give the same results for all simulation cases.

Test No. 1:

This represents a case where there is no remanence (residual) flux in the CT core. However, the CT current is with DC offset as can be seen from Figure 13. The measured transients show a high degree of distortion in the secondary current waveform due to CT saturation. A close agreement between the measured and simulated curves is observed. Note that the CT burden used is the rated burden for the tested CT.



Experimental:
1–primary current
2–secondary current referred to primary

EMTP Simulation:
3–CT Models #1 and #2
4–CT Models #3

Fig. 13. Results of Test No. 1: 600/5A CT; 2+j 3.5Ω; 4450 A; No Remanence

Test No. 2:

This case is similar to test no. 1, except the tested CT is of a different rating. The CT is driven into saturation starting with the second cycle and the secondary current peak remains low and distorted for the subsequent three cycles of the transient which are shown. The models can closely predict the saturated peak of the secondary current, and the distortion is accurately represented as shown in Figure 14.

Test No. 3:

The same CT as the one used in test no.1, is used in this test. However, this time a different burden and a primary current with a higher peak are selected. The simulation results obtained with all models agree with the measured transients. As seen from Figure 15, CT Models accurately represent the measured secondary current waveform.

Test No. 4:

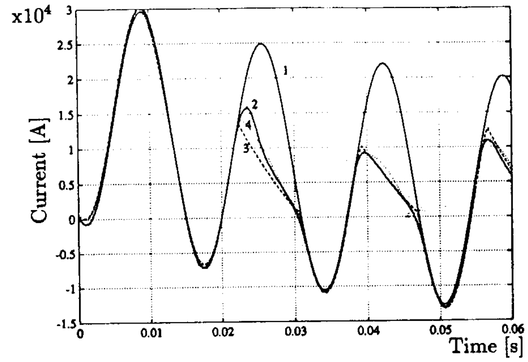
The CT used in this test is the same as in test no.2. The burden is an 8 ohm resistance, while the primary current remains at the same order of magnitude as in test no.2. In this test, the CT is driven into saturation early in the first half cycle and output current remains distorted for the remaining part of the test cycles. This transient is closely predicted by all the models as is evident from Figure 16.

Test No. 5:

The same CT as in the previous case is used in this test. A remanent (residual) flux is imposed on the CT prior to subjecting it to the transient. This is done in the laboratory by using a d.c. source of proper amplitude. Since the CT Models #1 and #2, which use the Type–98 nonlinear element model of EMTP, can not account for remanence, the simulations are run only using the CT Model #3. The measured and simulated waveforms given in Figure 17, show close agreement both in terms of the amplitudes and the distortions.

Test No. 6:

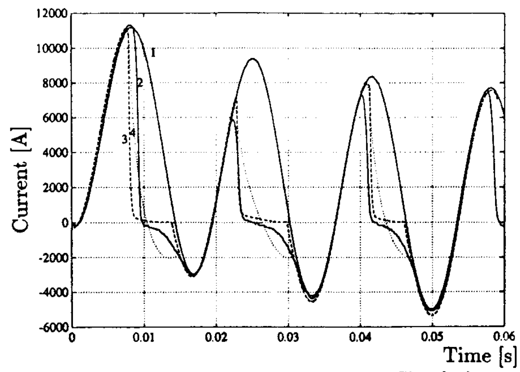
This case is identical to the test no. 5, except that the remanent flux imposed on the CT has a reverse polarity. The measured and simulated waveforms are shown in Figure 18.



Experimental:
1–primary current
2–secondary current referred to primary

EMTP Simulation:
3–CT Models #1 and #2
4–CT Models #3

Fig. 14. Results of Test No. 2: 2000/5A CT; 4+j7Ω;12690 A; No Remanence



Experimental:
1–primary current
2–secondary current referred to primary

EMTP Simulation:
3–CT Models #1 and #2
4–CT Models #3

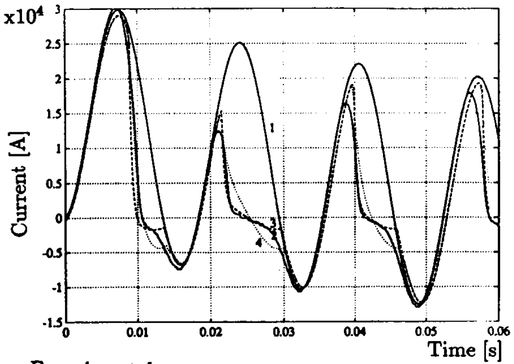
Fig. 15. Results of Test No. 3: 600/5A CT; 4Ω; 5120 A; No Remanence

The simulation results imply that all three CT models can represent the CT under diverse operating conditions with acceptable accuracy. Differences in amplitude and waveshape still exist and these are believed to be due to the method of measurement of the $V - I$ characteristics, as well as calculation of the $\lambda - i$ characteristics and the hysteresis generation. It is believed that even better accuracies can be obtained by further corrections in the EMTP source code.

CONCLUSIONS

This paper gives a comparison between transient responses obtained by performing tests on the actual CT and the ones obtained by digital simulation using EMTP. The following are conclusions of this study:

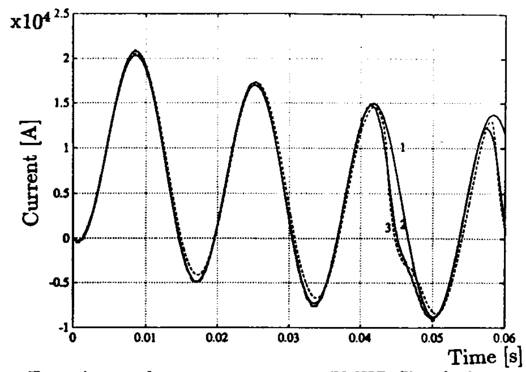
- EMTP–based CT models are a convenient way of simulating fault transient for relay study since they can easily be connected to an EMTP model of the power network.
- The existing models in EMTP for the single phase power transformer and the nonlinear inductor Type 98 can be used to build CT models.



Experimental:
1–primary current
2–secondary current referred to primary

EMTP Simulation:
3–CT Models #1 and #2
4–CT Models #3

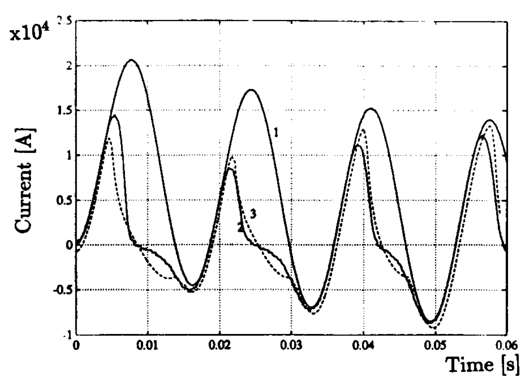
Fig. 16. Results of Test No. 4: 2000/5A CT; 8Ω; 12050 A; No Remanence



Experimental:
1–primary current
2–secondary current referred to primary

EMTP Simulation:
3–CT Models #3

Fig. 17. Results of Test No. 5: 2000/5A CT; 8Ω; 8380 A; with Remanence



Experimental:
1–primary current
2–secondary current referred to primary

EMTP Simulation:
3–CT Models #3

Fig. 18. Results of Test No. 6: 2000/5A CT; 8Ω; 7670 A; with Reverse Remanence

- **The existing element Type 96 which includes hysteresis and remanence may also be used to build the CT models if these phonomena are relevant in the studies.**
- EMTP–based CT models which use Type 98 element are sensitive to the change in the V–I curve slope. If the slope in the saturated region is high, the simulation results will not represent CT transient behavior well enough.
- CT models which use Type 96 element for the hysteresis representation are sensitive to the selection of saturated point needed for hysteresis generation. That point is not precisely determined for the V–I curve. Point selected in deeper saturation (exciting current above 2A) gives results that are closer to the actual values.
- Some differences between waveforms obtained by tests and by the simulations, shown in Figures 13–18, are mainly due to the mentioned problem related to the use of elements Type 98 and Type 96. This requires further investigation.

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DISCUSSION

Bruce A. Mork (Michigan Technological University, Houghton, MI), Don L. Stuehm (North Dakota State University, Fargo, ND): This paper provides a very useful overview and evaluation of current transformer modeling capabilities presently available in EMTP. Also of great importance were the transient performance tests carried out at a high power laboratory.

The authors present three equivalent circuits in Fig. 3. Were these models implemented using the single phase TRANSFORMER element, or using the type-18 ideal transformer? Since EMTP's TRANSFORMER requires a non-zero primary winding impedance, the type-18 element would seem well suited in cases like this where the primary winding impedance is near zero. Is the assumed value of 0.5Ω for the leakage reactance required to implement the TRANSFORMER element? Is it possible that L_2 and R_2 could have been measured by shorting the primary and performing a 60-Hz short circuit test from the secondary? If so, would the leakage reactance and the secondary winding resistance be greatly different from the values used?

The CT models presented here are essentially the same as those of a single phase power transformer. Past model evaluations for non-sinusoidal applied voltages showed performance to be extremely sensitive to core representation [1]. It was seen that type-98 core representation gave best model results over a wide range of excitation levels. Type-96 core representation gave good results for excitation corresponding to the voltage level at which the major loop was defined, but significant errors could occur above and below that voltage level. The authors provide additional valuable insight to this sensitivity, and have also managed to model the effect of residual flux. Could the authors explain how residual flux was specified in conjunction with the type-98 element?

The HYSDAT supporting routine in EMTP can generate a flux linked vs. current characteristic only for M4 grain-oriented core material. Specification of higher saturation points results in HYSDAT generating a wider major loop, corresponding to a higher level of excitation. This is clearly seen in Figs. 7 and 8.

In [1], it was found that the best way to determine the type-96 characteristic was not by using HYSDAT, but by constructing a characteristic from the normal magnetization curve having a loop width equal to the measured loop. In any case, performance problems were attributed to type-96 minor loop operation, and to the fact that the loop does not grow properly when excitation exceeds the defined major loop. In particular, loop width increases only in the "knee" area. Loop width does not increase at the waist of the loop, and the type-96 saturation point does not move to higher levels.

Could the authors briefly comment on which core representation they recommend at this point? Also, do they think that satisfactory performance can be obtained with existing EMTP model elements, or will improved core representations be required?

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M. Kezunovic (Texas A & M University, College Station, TX), Lj. Kojovic (COOPER Industries, Franksville, WI), A. Abur (Texas A & M University, College Station, TX), C. W. Fromen, D. R. Sevcik (Houston Lighting & Power, Houston, TX), and F. Phillips (Bonneville Power Administration, Walla Walla, WA): The authors would like to sincerely thank Dr. B. A. Mork and Dr. D. L. Stouthem for their adept interest in the material presented. The following clarification applies:

1. Type 18 Ideal Transformer was not used for CT modeling. All simulations were performed by using a Saturable Transformer whose magnetizing branch is internally represented by a Type 98 nonlinear element. Models #2 and #3 were developed with nonlinear elements, Type 98 and Type 96, connected externally to saturable transformer model. In these cases saturable transformer magnetizing branch was made dormant (no saturation was modeled).

2. The 0.5 Ω leakage reactance value was not required in order to implement the TRANSFORMER model. The actual value could not be precisely measured, and was only verified to be lower than 0.5Ω. Additional simulations were performed to determine the model sensitivity to this parameter. Results showed that the values between 0 and 0.5Ω do not influence the precision in the observed frequency range (up to approximately 10kHz). It is important to note that leakage reactance can not be accurately measured by simply shorting the primary, since bushing CTs are installed embracing the primary conductor (i.e., the CT itself does not have primary conductor, or if it does it is actually just a copper bar). The error obtained by such a measurement would be very high.

3. Residual flux was not included in Type 98 element. In cases when remanent flux is needed, Type 96 element can be used.

4. We agree that a more accurate way of constructing a hysteresis is to include data obtained by measurements directly in Type 96 element. This method was applied in the study.

5. Simulation of fault transients for relay studies can be conveniently carried out by the use of EMTP-based CT models. Both Type 98 and Type 96 elements can be used to build CT models. The results obtained during our study were not conclusive regarding selection of the core representation. An access to the EMTP source code would be needed to fully evaluate the present model limitations. It can be noticed that the signals simulated using the magnetizing branch representation differ from the actual measurement signals recorded during transient saturation period. Improved model precision would therefore require improved core representation.