Considerations in Applying EMTP to Evaluate Current Transformer Performance under Transient and High Current Fault Conditions

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Abstract— With addition of in-plant generation industrial facilities face increased short circuit levels and DC components in fault currents. EMTP is an effective tool in modeling and studying current transformer (CT) performance under such conditions. This paper advances the applications of EMTP for such studies. CT's models in EMTP may require hard-to-get information at early stages of power system projects. The paper examines approaches to make appropriate assumptions for missing model information and tests the sensitivity of EMTP results to such assumptions. By presenting case studies the paper facilitates such applications of EMTP and supplements an earlier IEEE Work Group on the EMTP modeling of protection CTs.

Keywords: Current Transformers, CT Saturation, EMTP, ATP.

I. NOMENCLATURE

CT(s): Current Transformer(s)
EMTP: Electromagnetic Transient Program
ATP: Alternative Transient Program
WG: Work Group (such as WG produced [6])

II. INTRODUCTION

IN addition to economics, protection systems are required to meet high standards of Reliability, Speed, and Selectivity [1]. The reliability facet reflects assurance of correct relay operation (dependability), and prevention of incorrect operation (security). Current transformers (CTs) are critical components for electrical protective relaying systems, as they convert the primary circuit currents into proportionately smaller currents that are suitable for input into the protective relaying system. In addition, CTs isolate such current inputs from the high voltage system. Accordingly, proper operations of the CTs ensure reliability and security of the protection system. Due to their importance, the performances of CTs under transient conditions have been the subject of interest to protection engineers as protection system studies have progressed over the past fifty years [2], [3], [4].

More recently, computer based mathematical models were developed to depict saturation and hysteresis in a transformer's iron core [5], [6]. With such developments, it became attainable to use different EMTP based programs (ATP, EMTPDC, and EPRI) to study CT's transients under different applications. An IEEE Working Group (WG) has prepared a detailed guide on the use on EMTP in such applications [7], [8]. However, for frequent applications, concerns arise about the ease of usage of such tools when some information listed in the WG Guide is not readily available. An example of information that is required for the WG model is the CT's core dimensions, and the CT saturation point used in the EMTP/ATP hysteresis routines. In the case of early stages of new installations or retrofitting existing facilities where short circuit would change (i.e. adding generation to existing buses), the core dimension information regarding the respected CTs may not be available. To carry out EMTP studies on CT's transient performance, under such conditions some assumptions would be utilized in lieu of the missing information. In some cases, such assumptions could be verified and adjusted as the missing information is obtained at later stages of design. In other cases, such assumptions would be required to stand on their own. Based on a large number of case runs for different ratings of CT's, this paper demonstrates the sensitivity of the study results to the different assumptions. Such manifestations would allow application engineers to establish fitting assumptions and promptly conduct the appropriate EMTP study.

The studies in this paper were conducted using the EMTP/ATP program [9]. Similar approaches could be applied for other programs.

III. CASE STUDY FOR CT'S EMTP APPLICATIONS

CT's in medium voltage switchgear with typical CT characteristics are considered as a study case to demonstrate the relevant application of EMTP. Considering a situation where a synchronous generator is added to an existing bus in industrial cogeneration facilities replacing a weak source. With high X/R ratio, the fault current on the bus not only it would be of a high magnitude but also it would include notable DC components. The DC components would contribute to the CT's saturation. With an intended simplification, the subject system is shown in Fig 1. The CT's accuracy and secondary resistance values are listed in Table 1. For the purpose of this paper, all listed typical CT's were examined. However, due to space limitations, the results of only few representing cases are included in the paper to depict the relevant topics of sensitivity analyses and associated selection of parameters.

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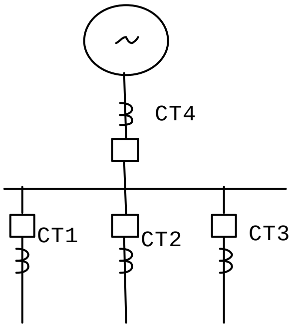

Fig. 1 Typical System for Applications of EMTP to Evaluate CT Performance

TABLE I
SELECTED CT’S FOR CASE STUDY

CT’s	Ratio	Nominal Accuracy	Secondary Resistance
1	600-5 A	C100	.25 Ohm
2	1200-5 A	C400	1 Ohm
3	2000-5 A	C400	.75 Ohm
4	4000-5 A	C600	1.25 Ohm

IV. PREPARATION OF CT MODELS FOR EMTP

The model should represent CT under all protection system conditions including those of high primary currents that include DC components. The DC components in the fault current would typically increase for faults near synchronous generators [10]. Such conditions result in CT core saturation as explained in [11], [12], [13]. Fig 2 depicts such a model [14]. Following [7], the EMTP could be applied as depicted in the following steps:

A. Preprocessor:

Instead of writing the full EMTP input file from scratch, a graphic based preprocessor could be used to initiate the basic input file. Such a file must be modified as discussed in following sub-sections of the paper. For the EMTP/ATP the program ATPDRAW could be used [15]. However, until CT’s comprehensive models are developed in ATPDRAW and other pre-processors, the preprocessor usage as depicted in [15] should be applied only to develop the circuit for the basic input file (skeleton file). Subsequently, it is necessary to adopt the WG methodology [7] and incorporate the CT’s specific characteristics. In the ATPDRAW circuit, a power source, as well as a CT burden (marked as RLC in Fig 3) should be selected to allow the development of ATP file that is suitable for modeling the CT. For the purpose of EMTP model, one 100 MVA synchronous generator (approximate rating) was selected as a power source. Three switches are inserted in the primary side of the CT circuit to simulate the application of 3-phase fault. The selection of 100 MVA synchronous generator with high X/R ratio allows the simulation of large fault currents with considerable DC components in some phases. The 3-phase short circuit is applied after 33 milliseconds (2 cycles) by simultaneously closing the three switches. By changing the three impedances in CT primary side, the fault current is adjusted for different study cases. The CT resistive burden is adjusted as listed in Table 1 to reflect different CT’s burdens.

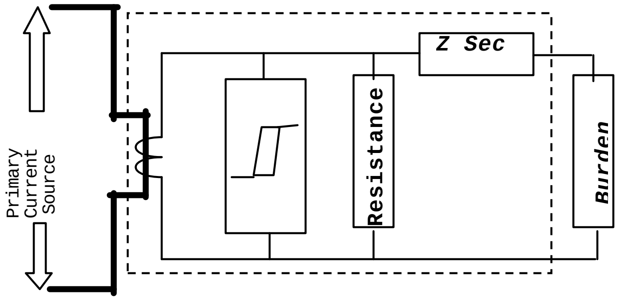

Fig. 2 Modeling CT as a Hysteresis Non-Linear EMTP Element

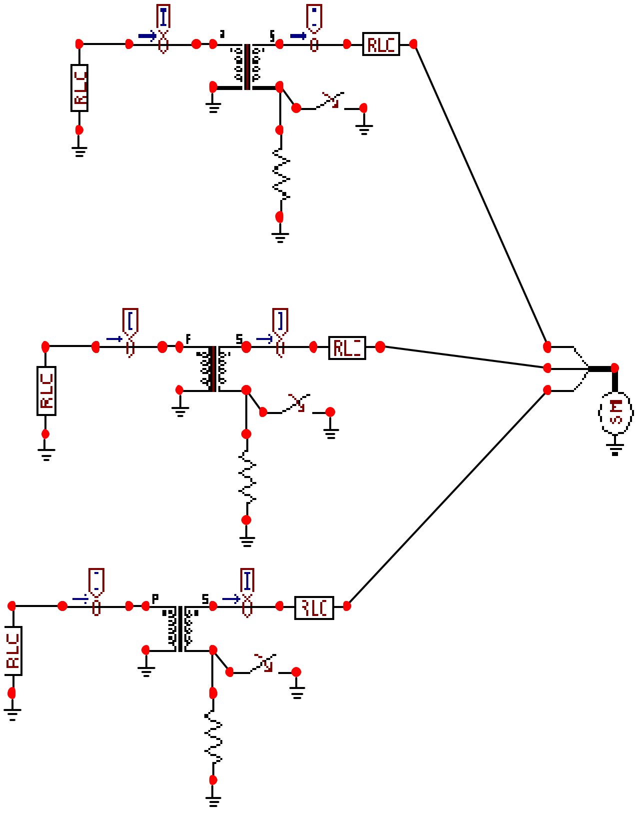

Fig. 3 ATPDRAW Model for 3 CT’s

B. Saturation Routine:

Traditionally, the suppliers of CT’s provide curves that reflect the factory test results in excitation current (rms) versus excitation voltage (rms) values as depicted in Fig 4. As an EMTP supplemental tool, the Saturation Routine was developed to convert the rms values of current and voltage in the CT saturation curves into peak current versus flux (Volt-s).

C. Hysteresis Routine:

The Hysteresis Routine was developed to address the remnant magnetization nature of an inductor with hysteresis characteristics (i.e. in equipment with iron core such as transformers and CTs). It produces a hysteresis loop that presents such characteristics where:

- Loop shape depends on the iron core material, and
- Loop dimensions depend on physical dimensions of the iron core and the number of turns.

In EMTP/ATP applications one type of silicon steel core material was embedded in the Hysteresis Routine. The sensitivity analyses performed in this paper use the Hysteresis Routine with its single type modeled silicon steel. Industry's improvement on core material (silicon steel) is continuous. Hence, in future sensitivity analyses, different characteristics may be modeled as suggested in Chapter IX (Future Work).

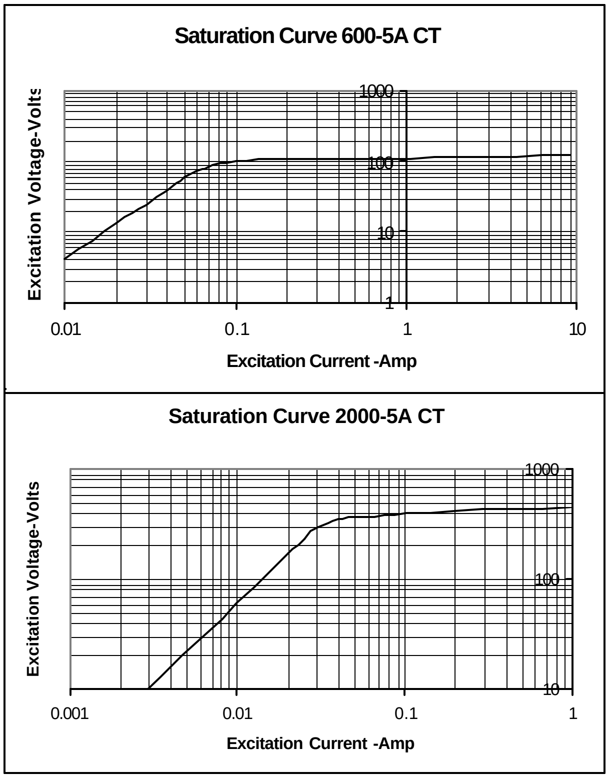

Fig. 4 Typical Manufacturer Supplied Characteristics Curves for 2 CT's

The physical dimensions of the CT are not readily available for each modeling case. As an alternate, the ATP RuleBook suggested to use the "Positive Saturation Point (PSP)" approach. The PSP is a point in the first quadrant where the hysteresis loop changes from being a multiple to a singled valued curve. Due to its importance to the hysteresis routine results, the PSP should be carefully selected. In Fig 4, two CT curves are shown. It could be observed that:

- In case of the 2000-5A manufacturer's curve, the flat area curve extended to 1 A which is in the order of approximately 30 times the knee current
- In case of 600-5A CT manufacturer's curve, the flat section of the curve extends to 9 A, which is in the order of approximately 150 time the knee current.

For both cases the saturation curve was converted to an EMTP saturation curve using the Saturation Routine. In the 2000-5A case, the selection of the-last-point-of-flat-part is appropriate (Fig 5). In the 600-5A case, a discussion is presented on three saturation-routine output points. The three points were the last three points in the 600-5 A CT saturation routine output corresponding to current value of 0.4956A, 1.684A and 23.68 A). The output of the saturation routine (one run) along with the hysteresis routine run outputs (three) are shown in Fig 6. From the graphs in Fig 6, it could be demonstrated that the run based on the point corresponding to 1.6484 A is the preferred run as:

- For the run based on .4956 A, the saturation curve extends outside the hysteresis loop.
- For the run based on 23.68A, the first point where the two legs of the hysteresis loop and the saturation curve meet is far from the program PSP

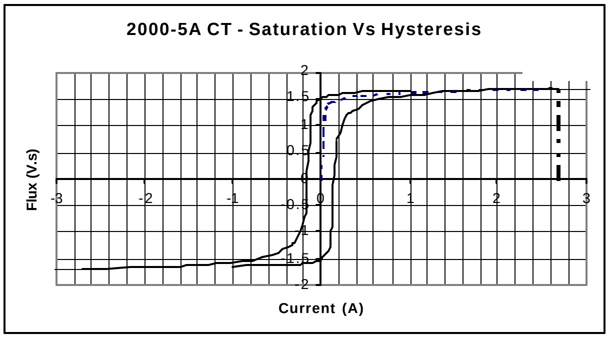

Fig 5: Saturation and Hysteresis Curves for 2000-5A CT

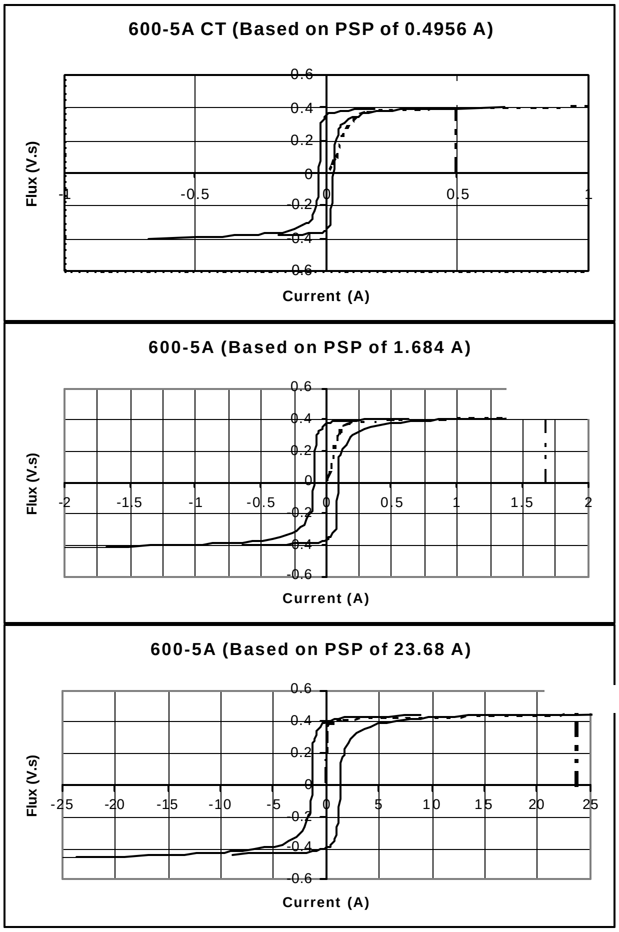

Fig. 6 Saturation and Hysteresis Curves for 600-5A CT

V. ASSUMPTION OF LDP & PERFORMANCE OF EMTP RUNS

The first quarter (positive X and positive Y) output of the

Hysteresis Routine could be inserted into the EMTP/ATP File as shown in Appendix C. The WG methodology [7] calls for the Last Data Point (LDP) of the hysteresis curve to be replaced with the point representing calculated CT's air core reactance. The air core reactance LDP could be calculated if the CT's dimensions are available. In the case of unavailable necessary physical dimensions:

- How would an arbitrary selected remote LDP be representative?
- How sensitive are the results of the EMTP runs for changes in the assumed LDP?

For the typical four CT's listed in Table 1, changes in both current values and slope of the LDP (flux value) are listed in Table 2.

TABLE 2

LAST DATA POINT VALUES IN TERMS OF DELTA A AND DELTA F

Delta A Ratio	Delta F ratio
30	10
30	20
40	10
40	20
50	10
50	20

Where:

Delta A Ratio: (LDP – NLDP) / (HLDP-NLDP) of Current

Delta F Ratio: (LDP – NLDP) / (HLDP-NLDP) of Flux

LDP: New Last Data Point

NLDP: Next to Last Data Point as calculated by Hysteresis Routine

HLDP: Last Data Point as calculated by Hysteresis Routine

Fig 7 depicts the primary and secondary currents of Phase C CT with LDP assumed to be with 3 values (Delta A ratios of 30, 40 and 50). Fig 8 shows the variation between the three secondary currents corresponding to each LDP. All currents are references to primary side, and all calculations are based on the same Delta F Ratio of 10. It is observed that although the absolute value of variations in secondary current is notable (4560 A referenced to primary side), the maximum errors in relative terms with respect to peak fault current of 57769 A is less than 8%. Also when Fig 7 and Fig 8 are examined together it would be noticed that the actual variations are in saturation timing, which bring the actual variations to relative values less than those given above.

The 2000-5 A CT on Phase-B would have a different variation, as the DC component on that phase is less than those on Phase-C. Fig 9 shows the variations for that phase.

In the case of varying Delta F Ratio, results will similarly vary. Fig 10 provides a comparison between Delta F Ratios of 10 and 20 when Delta A Ratio is selected as 40. It could be observed that the variation is in the same order of magnitude as the Delta A Ratio variations.

VI. EXAMPLES OF RESULTS FOR VARIOUS CTS

A. *CT with Ratio 4000-5A:*

This 4000-5A CT was examined using LDP with delta A ratio of 40 and delta F of 10. Two secondary resistance burdens were used: 2.34 and 4.68 Ohm. The results of the EMTP runs for phases A and B are shown in Fig 11.

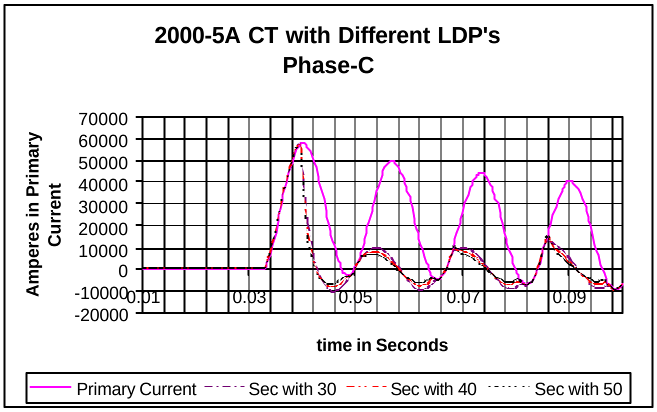

Fig. 7 Secondary Current of Ph-C Reflected to Primary @ Various LDP

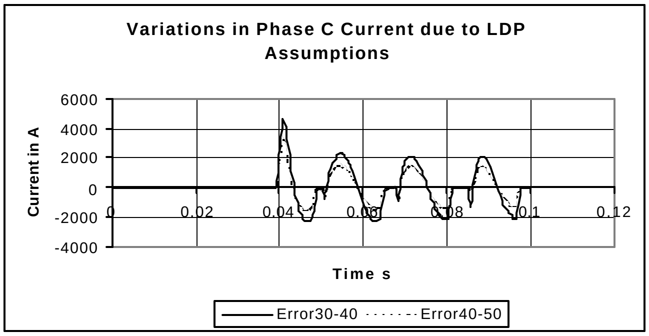

Fig. 8 Variations in Ph-C Secondary Reflected to Primary Current

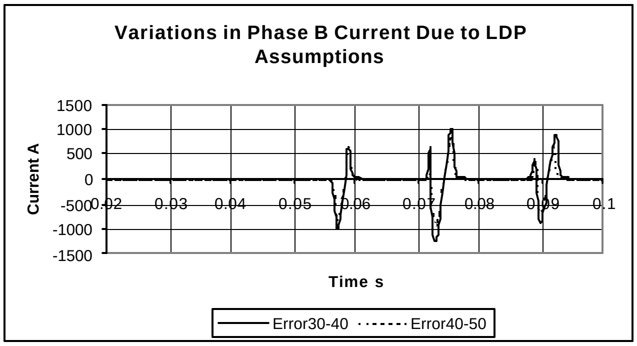

Fig. 9 Variations in Ph-B Secondary Reflected to Primary Current

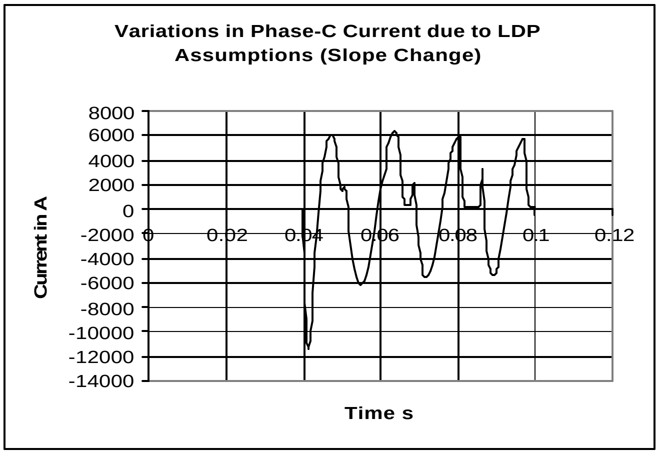

Fig. 10 Variations of Secondary Current of Phase-C with variations of Delta F Ratio from 10 to 20

It could be observed that:

- For Phase-A: DC component in the fault current is high. Accordingly, the CT saturates. However, when the burden is only 2.34 Ohm, the saturation starts after the first cycle, while for the higher burden of 4.68 Ohm, the saturation starts at the later part of the first cycle.

- For Phase-B: saturation does not occur, as the DC component is not significant.

B. CT with Ratio 1200-5A:

This 1200-5A CT was also examined using LDP with delta A ratio of 40 and delta F of 10. Two secondary resistance burdens were used: 2.34 and 4.68 Ohm. The results of the EMTP runs for phases B and C are shown in Fig 12.

It could be observed that:

- For Phase-B: DC component is not significant, however the fault current is large enough (with respect to the CT's ratio) that mild saturation occurs.
- For Phase-C: DC component in the fault current is high. Hence saturation occurs in less than ½ cycle with 2.34-Ohm burden. When the burden is doubled, saturation occurs in the first quarter of the first cycle.

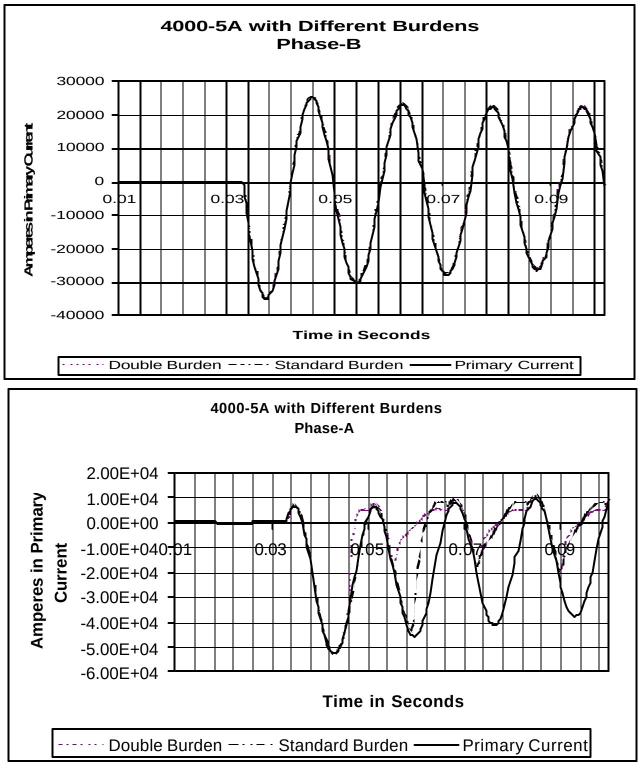

Fig. 11 CT 4000-5A with Two Secondary Burdens 2.38 and 4.68 Ohms

In summary both sensitivity and current waveform analyses show the appropriateness of Delta A and Delta F selections for the above two sets of CT's. Similar analysis would be required for other sets of CT's with other burdens.

VII. Conclusions

EMTP could be a very valuable tool in evaluating the performance of current transformers that are subjected to high currents and DC current components under fault conditions. Even with data such as CT's dimensions is missing at the earlier stages of design, useful ETMP modeling and analysis could still be carried out. To optimize the CT modeling in EMTP, selectivity and sensitivity analysis approach could be used. Examples are given for the selection of acceptable ranges of Positive Saturation Points (PSP's) and Last Data Points (LDP's). Sensitivity analysis confirms suitability of selected model parameters. Proposed approach is established by studying numerous typical CTs and completing full modeling and EMTP analyses on each of them.

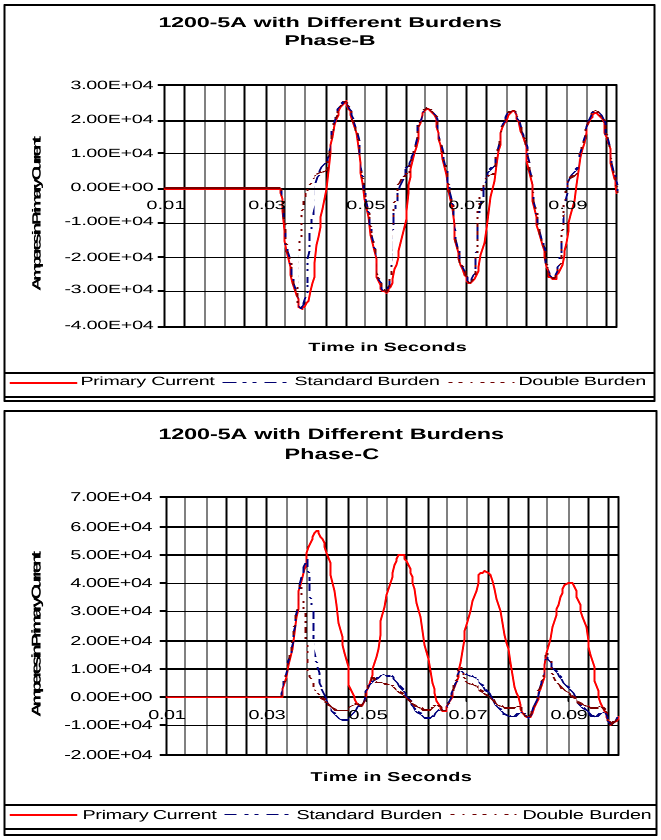

Fig. 12 CT 1200-5A with Two Secondary Burdens 2.38 and 4.68 Ohms

VIII. Future Work

Future work includes first Comparison of results of sensitivity analysis with EMTP runs based of CT's data with known core dimensions. Second, the future work would include the performance of sensitivity analyses for different modeled core material used in present CT's fabrication and establish the impact of selecting typical material on the CT modeling in EMTP.

IX. Appendices

A. EMTP Saturation Routine (Typical)

```
BEGIN NEW DATA CASE
C  CT Saturation Curve for 1200-5 C400 CT
C  Use Vbase as 1V= 0.001 kV, and Ibase as 1A,
C  MVA Base as .000001 MVA
SATURATION
$ERASE
C  Freq     Vbase  MVAb
    60.   1.E-3   1.E-6      1
C    Irms Amp          Vrms
       0.001000           2.5
       0.010000           60.0
       0.024000           250.0
```

```
    0.031000       350.0
    0.050000       450.0
    0.100000       490.0
    0.900000       510.0
       9999
C Final row of resulting printout:
$PUNCH, CT_Sat.pch
BLANK card ending all  "SATURATION"  data cases
BEGIN NEW DATA CASE
BLANK
```

B. EMTP Hysteresis Routine (Typical)

```
BEGIN NEW DATA CASE
C         This will use Hysteresis supporting routine
HYSTERESIS
C  ITYPE   LEVEL   { Request Armco M4 oriented silicon steel -- only 1 available
     1      4   { That was ITYPE=1.  As for LEVEL=2, moderate accuracy output
   .226   1.838     { Current and flux coordinates of positive saturation point
$PUNCH
BLANK card ending "HYSTERESIS" data cases
BEGIN NEW DATA CASE
BLANK
```

C. Part of EMTP Program, where CT Hysteresis Inserted

```
BEGIN NEW DATA CASE
C --------------------------------------------------------
C Generated by ATPDRAW  November, Saturday 27, 2004
C A Bonneville Power Administration program
C Programmed by H. K. Høidalen at SEfAS - NORWAY 1994-2003
C --------------------------------------------------------
C  ATP Case for CT of 1200-5A C400 Resistance Burden 2.34 Ohm, using hys
C  dT  >< Tmax >< Xopt >< Copt >
  1.E-6     .1
    500      1      1      1      1      0      0      1      0
C      1        2        3        4        5        6        7        8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
/BRANCH
C < n 1>< n 2><ref1><ref2>< R  >< L  >< C  >
C < n 1>< n 2><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
C                      I0    F0          Rmag
 TRANSFORMER            .38801.4639TX0001  1.E4                          0
      .1780000     .602032353
      .1958000     .832717647
      .2492000     1.12529412
      .3204000     1.35035294
      .3880400     1.46288235
      .5073000     1.57541176
      .6942000     1.67668824
      .9523000     1.75545882
      1.246000     1.81172353
      1.780000     1.86798824
      2.848000     1.91300000
C       3.916000     1.92425294 (Last Point to be replaced)
      45.56800     2.02552940
         9999
```

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XI. BIOGRAPHIES

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