

Saturation of Current Transformers and its Impact on Digital Overcurrent Relays

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Abstract—improper selections of current transformers will result in CT's saturation during fault conditions which can affect protection relays operations. With the absence of clear and practical guidelines for CT's selections, designers are facing great difficulties to ensure proper operations of digital relays. The impact of CT saturation is different for different protection devices and schemes. This paper investigates the influence of CT saturation on overcurrent digital relays, in distribution systems where loads are relatively small and connected to switchgears with high short circuit levels. A research was performed to verify the operations of instantaneous and time-delayed overcurrent digital relays to ensure coordination with other devices and safe isolations of faults. It is shown that instantaneous digital relays will perform properly with a relatively small CT's. A criterion for selecting CT's for instantaneous digital overcurrent relays operations is presented. However, time-delayed overcurrent relays will be significantly impacted by CT's saturation and special care shall be taken to achieve coordination with other devices.

Index Terms: CT, EMTP, Hysteresis, Overcurrent Relays, Saturation, Transient Response.

I. INTRODUCTION

IN the electrical distribution systems, saturation of low ratio current transformers (CTs) at high fault current locations may cause misoperation of overcurrent relays. It has been reported that relays act differently during CT saturations and their response may not meet the published time-current characteristics [1-7]. These problems can cause severe loss of production to various plants or damages to critical electrical equipment. The IEEE guide for the application of current transformers (IEEE Standard C37.110) contains steps to avoid the effects of AC and DC CT saturation [8]. However, many of these steps result in large CTs, which are not economically acceptable. In Practice, many small loads may be connected to a bus, with inherently high short-circuit currents; usually have CT's with low ratios.

Fig. 1 shows two examples of low CT's ratios connected to a bus with high-short circuit level. A transformer with full load current of 43.7 A, with 50/5 CT that is adequately protected against overload is also shown.

However, the short circuit rating is 300 times the CT rating. This will result in either partial or full CT's saturations that may effect the overcurrent relays operations. Similarly, a motor with an overload protection with 100/5 CT is shown. Also, a concern is raised about the instantaneous and time-delayed overcurrent relay response for high short circuit level as the short circuit currents can exceed 150 times the CT rating.

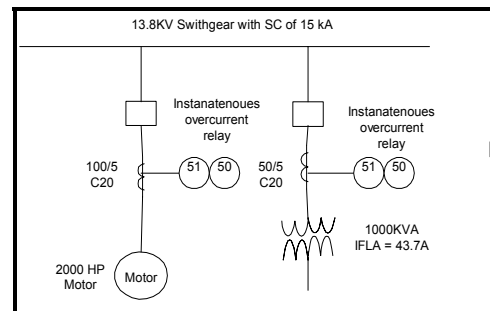


Fig. 1. Typical Distribution System with Low CT Ratio and High SC Level

One method of avoiding the CT saturation is to increase the CT's core size. The CT's dimension will be a limiting factor and will make the installation of such a CT in switchgears impractical. This paper will investigate the transient behavior of CT's and the impact of their saturation on digital overcurrent relays during high fault levels. The paper will also analyze the effect of different classes and sizes of IEEE/ANSI C-class CT's on typical digital overcurrent relays as most protection devices make operations decisions based on the RMS values calculated by the relay. The transient saturable transformer models available in EMTP were validated in the laboratory to ensure proper selection of the CT's models. Moreover, different fault scenarios, implemented through EMTP, were converted in a common-trade file in order to conduct tests to analyze the transient behavior of digital overcurrent relays. The effects of CT saturation on digital overcurrent relays are evaluated by conducting various laboratory tests on a typical microprocessor-based overcurrent relay.

II. CURRENT TRANSFORMERS MODELING

Pseudo-nonlinear reactor model (Type-96) in the EMTP and ATP) accounts for the Hysteresis effects in the transformer core and allows for analyzing the effects of residual flux left in the CT following primary current interruption. Many papers

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showed that the EMTP nonlinear inductor (Type-96) is very effective in analyzing the relay performance under transient conditions in order to assure a high degree of dependability and security in their design and applications [9-15]. The C37.110 1996 contains rules for selection of CT's to avoid AC and DC saturations. To avoid AC saturation, the CT shall be applicable of a secondary saturation voltage:

$$V_x \geq I_s \cdot Z_s \quad (1)$$

Where: I_s is the primary current divided by the turns ratio

Z_s is the CT secondary burden

V_x is the CT saturation voltage

Current transformer secondary terminal voltage rating is the voltage that the CT will deliver to a standard burden at 20 times rated secondary current without exceeding 10% ratio correction. Therefore, (1) can be rewritten as follows:

$$20 \geq i_f \cdot z_b \quad (2)$$

Where: i_f is the maximum fault current in per unit of CT rating and z_b is the CT burden in per unit of standard burden

In addition, C37.110.1996 highlights the criteria to avoid saturation with a DC component in the primary wave as follows:

$$V_x \geq I_s \cdot Z_s \left(1 + \frac{X}{R}\right) \quad (3)$$

Where: X and R is the primary system reactance and resistance up to the point of fault. Similar to the AC saturation, (3) can be rewritten as follows:

$$20 \geq \left| \frac{X}{R} + 1 \right| \cdot i_f \cdot z_b \quad (4)$$

Where: i_f is the maximum fault current in per unit of CT rating; z_b is the CT burden in per unit of standard burden and X/R is the system X/R ratio.

III. IMPLEMENTATIONS OF CURRENT TRANSFORMERS MODEL

A. Current Transformers Transient Analysis

For the purpose of transient analysis, the equivalent circuit of Fig. 2 is used. To investigate the nonlinear behavior of the CT's, the magnetizing leg of the current transformer can be represented in Fig. 3 to visualize the non-linear phenomenon of the magnetizing circuit. For each level of excitation, a different value of reactance is used. In Fig. 3, three B-H diagrams are shown, as flux versus magnetizing current I_m , representing low, medium and high level of excitation.

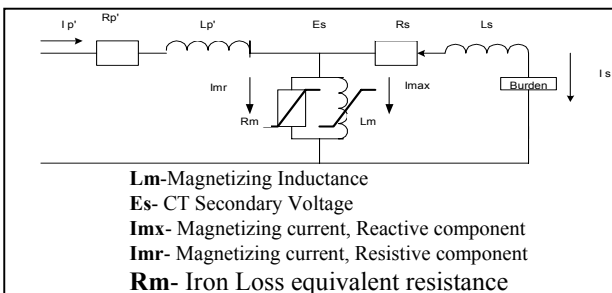


Fig. 2 Equivalent circuit for non-ideal current transformer

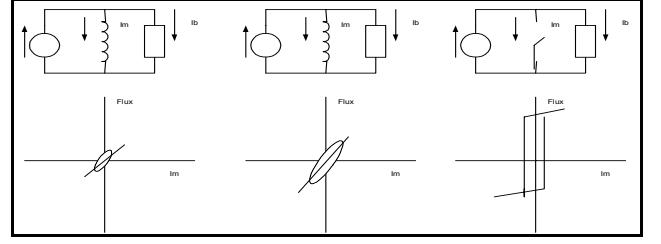


Fig. 3 CT equivalent circuits at various levels of excitation

B. Mathematical Model for CT's Core Representation

The measure of a CT performance is its ability to reproduce accurately the primary current in secondary terms both in wave shape and in magnitude. There are two parts: (1) the performance under the symmetrical ac component, and (2) the performance under the offset dc component.

In order to model the CT, the following shall be undertaken:

- Conversion of the rms V - I saturation curve data into peak ψ - I data with the Hysteresis loop being ignored.
- Providing the Hysteresis loop data required by the Type-96 Pseudo-nonlinear reactor model.

The nonlinear characteristics are computed according to the following assumptions:

- The ψ - I curve are symmetric with respect to the origin (L_k is the slope of segment k of the ψ - I curve).
- The winding resistance and leakage inductances are ignored in the analysis.

The algorithm uses data points from the CT secondary excitation curve V_{rms} - I_{rms} to calculate the peak ψ - I curve. The results is a piece-wise linear model because a small finite number of data points are used, usually 10 or less. The conversion of rms voltage values to flux is only a rescaling procedure. For each linear segment in the ψ - I curve,

$$\varphi_k = \frac{\sqrt{2}V_k}{\omega} \quad (5)$$

Assuming that $\varphi_k(\theta) = \varphi_k \sin \theta$, then for the following segments ($k \geq 2$), the peak current is obtained by evaluating for I_{k-rms} for each segment k , using (6):

$$I_{k-rms}^2 = \frac{2}{\pi} \left(\int_0^{\theta_1} \left(\frac{\varphi_k \sin \theta}{L1} \right)^2 d\theta + \int_{\theta_1}^{\theta_2} \left(I_1 + \frac{\varphi_k \sin \theta - \varphi_1}{L2} \right)^2 d\theta + \dots \right) \quad (6)$$

$$+ \int_{\theta_{k-1}}^{\pi/2} \left(I_k + \frac{\varphi_k \sin \theta - \varphi_{k-1}}{L_k} \right)^2 d\theta$$

Only the last segment L_k is unknown. Therefore, (1) can be rewritten in the form:

$$a_{lk} Y_k^2 + b_{lk} Y_k + c_{lk} = 0 \quad (7)$$

If constants a_{lk} , b_{lk} , and c_{lk} are known, and $Y_k = 1 / L_k$ can be computed. Y_k can then be solved from 7 and it must be positive. The peak current i_{lk} is computed from (8):

$$i_k = i_{k-1} + Y_k (\varphi_k - \varphi_{k-1}) \quad (8)$$

Then, one point is entered in the subroutine HYSTERESIS in the ATP to provide the hysteresis loop data for the current transformer [15].

C. Laboratory Validations of Current Transformer Developed Model

Laboratory tests were conducted for model validation purposes. Primary advanced injection test equipment (Omicron-CPC100) has been utilized to carry out different kinds of testing for the current transformer. This device can inject up to 2000A primary [15]. In addition, it is a software-based device that can provide the automatic capability to implement, CT Excitation tests. In the testing setup, a digital relay (Basler Overcurrent Relay BE1-951) has been used in the tests to trace and capture the secondary signals for the CT with sampling rate of 12 samples per cycle. A current transformer, with 50/5 ratio and ANSI/IEEE class C20, has been tested to obtain the actual excitation curves to be implemented in the EMTP. The CT has been driven to saturation and secondary current has been captured by Digital Events Recording feature in the microprocessor-based relay. All laboratory data was compared with EMTP results to validate the results and ensure having proper modeling for the current transformer.

An excitation test has been conducted, first, on the selected CT in order to obtain the actual excitation curve. The test was implemented by injecting current in the secondary side of the 50/5 CT. The V-I curve is shown in Fig. 4. The selected CT has a class of C20. Therefore, the maximum burden is 20/100 or 0.2 ohm. This burden does not include the secondary resistance of the current transformers. Table I shows the effects of the connected burden on the current transformer saturation and its capability to reproduce the primary signal on the secondary side.

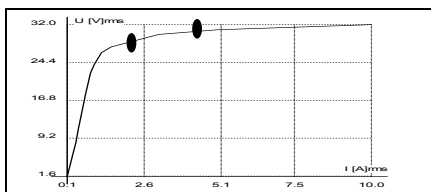


Fig. 4. Laboratory excitation curve for 50/5CT

Fig. 5 shows CT transient response with different burden values connected. Effects of CT saturation are shown in case-3 where the primary current is not accurately reproduced in the secondary. Fig. 6 compares between the laboratory results and EMTP model with 31V saturation voltage in the three cases, listed in Table I. It is shown that EMTP based CT models, using non-linear inductor model (Type-96) are a convenient way of simulating fault transient for relay study.

TABLE I
CASES APPLIED IN THE LAB TO EXAMINE THE BURDEN EFFECT ON CT'S

Primary Injected Current	Total Burden (Ohm)			Effect on Secondary Current
	Case	R	X	
17.4 X CT Rating Current (870 RMS Current)	Case 1	0.3	0.302	Initial Saturation of CT. The output signal is slightly distorted.
As per IEEE/ANSI C37.110, Section 4.4.1, Saturation Voltage is , $V_s = I_s * (R_s + Z_b) = 87.5 * (0.0607) = 37.2V$				
13 X CT Rating Current (652 RMS Current)	Case 2	1.0	1.508	Output signal is not sinusoidal anymore. More distortion in the signal.
As per IEEE/ANSI C37.110, Section 4.4.1, Saturation Voltage is , $V_s = I_s * (R_s + Z_b) = 65 * (1.809) = 117.6V$				
13 X CT Rating Current (626 RMS Current)	Case 3	5.0	6.786	Severe Saturation of CT. Low secondary current is reflected.
As per IEEE/ANSI C37.110, Section 4.4.1, Saturation Voltage is , $V_s = I_s * (R_s + Z_b) = 65 * (8.429) = 547.9V$				

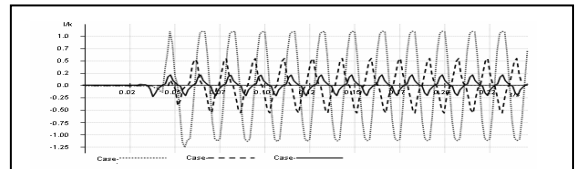


Fig. 5. Laboratory test results obtained for all cases

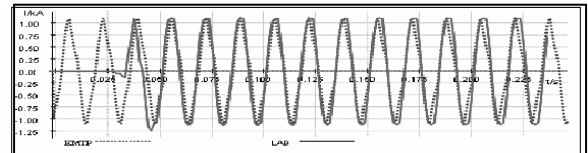


Fig. 6. Comparison of EMTP and Lab results for cases 1

IV. TESTING THE EFFECTS OF CURRENT TRANSFORMERS ON DIGITAL OVERCURRENT RELAYS

The following cases were used to investigate the performance of the digital overcurrent relays:

- Secondary burden.
- Short circuit level.
- The X/R ratio (DC offset).
- The remnant flux.

A. Effects of Symmetrical Current on Relay Operation

The evaluation of digital relays performance resulting from CT saturation on symmetrical AC current input will be conducted considering the following two factors:

- Current transformer burdens.
- Symmetrical fault current magnitude

Table II summarizes the study cases, developed by EMTP for different CT secondary burdens that will be injected to the Basler overcurrent relay by the secondary test equipment OMICRON CMC 256. The burden is primarily due to CT windings and external leads to the relay. In all three cases, it

has been assumed that the full circuit runs of #10 AWG (1.0 Ω / 1000-ft) are 250 ft, 500 ft and 2000 ft respectively.

TABLE II

CASES APPLIED TO EXAMINE THE BURDEN EFFECT ON DIGITAL RELAYS CT'S

Primary Injected Current To EMTP 50/5 CT model	Burden		
	Case	Value (Ohm)	Multiple of standard burden
20 X CT Rating Current (1000 RMS Current)	Case 1	0.25	1.25
	Case 2	0.5	2.50
	Case 3	2.0	10.0

Fig. 7 compares the simulated current and actual relay response for the worst case (Case 3) where 10 times the standard burden is used. As a result, severe saturation of secondary current is observed. The magnitude and shape of the current signal is severely affected as shown in the simulated EMTP current. The current magnitude is reduced to about 75% of the secondary current magnitude. The shape of the signal is severely distorted, although the primary current is pure sinusoidal. The response of the digital relay shows around 16% reduction in the current magnitude is again observed.

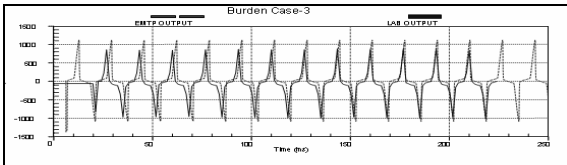


Fig. 7 Simulated EMTP Current versus Relay Current Response in Case-3 (Reflected at Primary of 50/5 CT)

B. Effects of Asymmetrical Current Relay Operations

Since most of faults involve DC components, it is very necessary to study the impact of asymmetrical faults on the CT and the associated effects on microprocessor-based overcurrent relays. Table III presents a summary of the cases to study the impact of asymmetrical fault current on the operation of the relay. All cases are developed based on 0.5 Ω (2.5 times standard burden).

TABLE III

CASES APPLIED TO EXAMINE THE X/R RATIO EFFECT ON DIGITAL RELAYS

Case	Primary Injected Current To EMTP 50/5 CT model Current	Time Constant	X/R Ratio	Saturation Voltage Using Criteria $20 \geq \left \frac{X}{R} + 1 \right \cdot i_f \cdot z_b$
1	3.25 x CT rated Current	0.064 s	24	203.1
2		0.042 s	16	138.1
3	20 x CT rated Current	0.064 s	24	1250
4		0.042 s	16	850

A sample of simulated secondary current results is shown in Fig. 8 (For case-3). In this case, very high current is injected

to the primary of the CT (20 X CT) with the same secondary burden and with X/R ratio of 24. The CT is driven into severe saturation within the second cycle and the secondary current remains low and distorted for the three cycles. The response of the relay to the injected current was almost identical, in terms of shape as shows. The magnitude of the relay current response had a reduction of about 5%, compared to the simulated current.

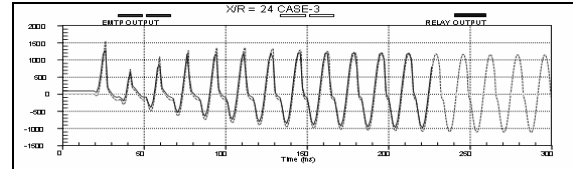


Fig. 8. Simulated EMTP Current versus Relay Current Response in Case-3 (Reflected at Primary of 50/5 CT)

C. Evaluations of Instantaneous Digital Relays Responses

From Table IV, the trip time for a digital overcurrent relay will be 4.7 and 4.1 cycles, including the required time for the relay to operate for asymmetrical faults with X/R ratios of 24 and 16 respectively with a proposed instantaneous setting of 400A. The operation of the relay is fairly acceptable as coordination with upstream protective devices can be achieved. The relay response is shown in Fig. 9.

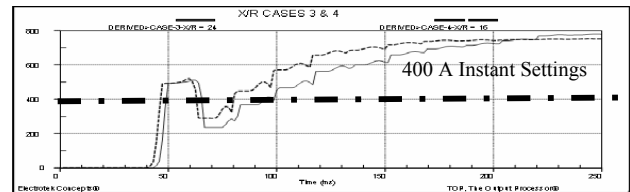


Fig. 9. Response of Relay with 400 A Instantaneous Setting for Cases 3 and 4

TABLE IV
RELAY OPERATION TIME FOR 400A INSTANTANEOUS SETTINGS WITH 16 AND 24 X/R RATIO

Instant. Current Setting (A)	Case	Trip time delay		Calculated Saturation Voltage Using (4)
		Second	Cycles	
400A	Case 3 X/R = 24	0.078	4.7	1250
	Case 4 X/R = 16	0.068	4.1	850

D. Evaluations of Time-delayed digital relays response results

CT saturation does not only impact the operation of instantaneous overcurrent digital relays. It also affects the time-delayed operation of digital overcurrent relays. The impact of the symmetrical and asymmetrical faults, resulting in CT saturations on digital overcurrent relays will be analyzed based on the laboratory tests results, shown in

previous sections. For the purpose of analysis, A Basler digital overcurrent relay- long inverse (L2) time-current characteristic is considered for evaluations purposes. A curve with 50A pickup is considered. Study cases presented in Table III will be considered for evaluations. For example, in the worst scenario cases 3 and 4, shown in Table IV, 1000A primary current was injected to the 50/5 CT. However, lower current was seen by the relay for both cases, with considerable time delay as shown in Fig. 10. This has been calculated and added to the time delay of the ideal case. The calculated time delay values are presented in Table V for both cases. Fig. 10 shows that a time delay of 0.27 and 0.12 seconds will be experienced for cases 3 and 4, in comparison to the ideal case.

Based on the test results, it has been concluded that the instantaneous digital overcurrent relays can operate with low CTs, under certain applications and conditions. On the other hand, time-delayed digital relays will be significantly affected by CT saturation, although the significance of the saturation varies, depending on the fault level, system X/R ratio, secondary burden and remnant flux in the core.

TABLE V
EFFECTS OF ASYMMETRICAL FAULT ON TIME-DELAYED DIGITAL RELAY
(CASE3&4)

Case	Secondary current seen by the digital relay when 1000A primary fault occurred	Operation time (Seconds)	Time difference (Seconds)
Ideal Case	100A	0.18	0
X/R = 24, case-3	75A	0.45	0.27
X/R = 16, case-4	77A	0.3	0.12

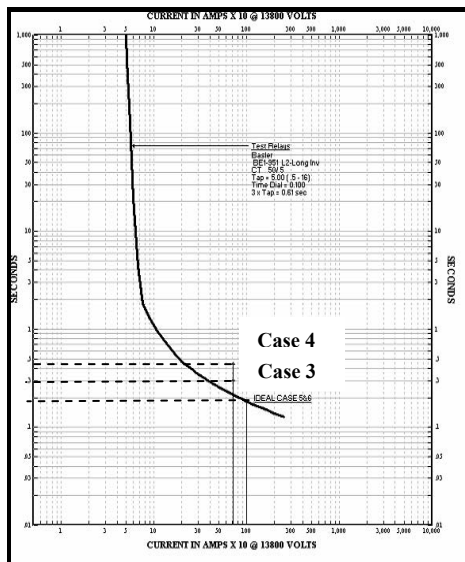


Fig. 10. Impacts of Asymm Fault on Time-delayed Digital Relays (Case 3&4)

V. STUDY CASE AND APPLICATIONS

A case study will be considered to show the area of applications of the paper findings. A transformer with

1000KVA rating will be considered. The secondary burden is made of 0.1 Ω or 100 ft of # 10 AWG control wires. The system X/R ratio is 6. A digital overcurrent relay is installed on the high-side of the transformer to protect against overload and short circuit. The CT is sized based on the full load current of the transformer which is 41.8 A. A 50/5 CT, with accuracy class of C20 is selected as shown in Fig. 11.

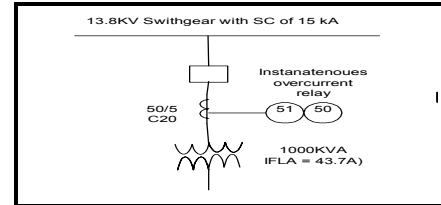


Fig. 11. Case study for a feeder to a transformer with 50/5 CT

From results, it has been proven that the digital overcurrent relay will operate with 50/5 CT, C20 with instantaneous settings of 400A with no more than 4.7 cycles time delay, if the burden voltage of 1250 is met. This criteria will be utilized to check the adequacy of the selected CT with the available short circuit level

$$1250 \geq \left| \frac{X}{R} + 1 \right| \cdot i_f \cdot z_b \quad (9)$$

The maximum fault current with 400 A instantaneous settings can be calculated using the following formula:

$$I_{MAX} = \frac{ANSIClass}{100 \cdot Z_b} \cdot \frac{V_{Burden}}{\left(1 + \frac{X}{R}\right)} \cdot CT_{Rating} \quad (10)$$

The maximum fault that to ensure secure operation can be obtained from (10):

$$I_{MAX} = \frac{20}{100 \cdot 0.1} \cdot \frac{1250}{(1+6)} \cdot 50 = 17,857.1A \quad (11)$$

The instantaneous operation of 50/5 CT can be guaranteed with 357 times CT rating with 6 X/R ratio. Fig. 12 shows the response of the relay with 15,000A short circuit current for the case presented. It confirms that the instantaneous digital relay, with 400 A instantaneous settings, will respond to the fault in this case with no more than three cycles.

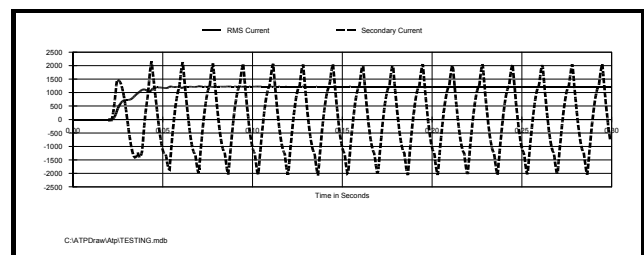


Fig. 12. Case Study with X/R=6, Burden =0.1 and Primary Current of 15,000 A

For comparison purposes, IEEE C37.110-1996 will be considered for sizing the CT's in the case study. Equation (4) shall be met. To meet the requirements CT of ratio 600/5 and accuracy class of C100 is required. Substituting in (4)

$$20 \geq |6+1| \cdot 25 \cdot 0.1 = 17.5 \quad (12)$$

VI. CONCLUSIONS AND RECOMMENDATIONS

An acceptable and precise current transformers model was implemented, using the non-linear inductor model (Type-96) in EMTP. The model is a very convenient way to test the transient behavior of the CT's and digital overcurrent relays. This model was validated and tested in the laboratory to ensure appropriate and accurate suitability. The selection of CT could be based on the operating time of the instantaneous relays. CT's subjected to 100 times fault current, for example, could work with no problem and without meeting the criteria of IEEE standard C37.110-1996. CT's driven to saturation, can still provide sufficient current to the instantaneous digital overcurrent relays. On the other hand, time-delayed digital relays will be significantly affected by the CT saturation, although the significance of the saturation varies, depending on the fault level, system X/R ratio, secondary burden and remnant flux in the core. However, more ideas are to be examined by conducting further investigation on time-delayed digital overcurrent relays to come up with criteria for calculating the time delay caused by saturation for consideration in the relay coordination. This will provide more flexibility to achieve coordination with under-sized CT's by taking into consideration the time delay, resulted from the CT's saturation.

For CT's that will be used with instantaneous digital overcurrent relays, the following practical approach for CT's selections is recommended:

1. Select the CT ratio based on the load requirements.
2. Calculate the required instantaneous relay settings.
3. Use (4) to calculate the V_s .
4. Run EMTP model for the CT to ensure proper operations of the relay at the instantaneous settings. Calculate the time required for the relay to operate and investigate if it is acceptable. Otherwise, change the CT ratio or accuracy class to higher ones.
5. For the same CT, define a criteria for CT selection by using the calculated V_s and calculate the maximum fault current based on the secondary burden and X/R ratio

VII. ACKNOWLEDGEMENTS

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IX. BIOGRAPHIES



Ibrahim El-Amin is a Professor of Electrical Engineering at the King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia. He received his Ph.D. and MSc degrees from the University of Manchester in 1978 and 1975, respectively, in electrical engineering with a specialization in power systems. He obtained his B.Sc. degree in electrical engineering from the University of Khartoum, Sudan, in 1971. Since joining KFUPM in 1978, Dr. El-Amin has taught undergraduate and graduate courses in electrical power systems and electrical machines, and has been actively involved in both basic and applied research in the area of power systems. His research interests include power systems, DC transmission, power quality, power electronics, and the integration of alternative energy sources into power networks. Dr. El-Amin has published a large number of technical papers and reports. Dr. El-Amin was an active member of the research team which conducted the project "Feasibility Study for

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