CT Modeling Techniques for Relay Protection System Transient Studies

Ljubomir A. Kojovic
Cooper Power Systems
Franksville, WI, USA
(E-mail: lkojovic@cooperpower.com)

***Abstract-* This paper presents simplified modeling techniques to model current transformers and power system areas involved in faults to study the impact on relay protection systems. The modeling techniques are easy to implement and provide good results. To support validity of the methods, three cases of protection system misoperation are included in this paper. Simulation results were also compared against laboratory tests and current waveforms recorded by digital fault recorders.**

Keywords: Current Transformer, Saturation, Transient Study, Protective Relaying, Digital Simulation, Modeling

I. INTRODUCTION

In an actual power system, short circuit currents may have a significant DC offset which can saturate current transformers (CTs) at several times rated current. Remanence in the CT core can also contribute to CT saturation. If the CT characteristics are not properly selected for fault conditions, saturation will occur, and relays can misoperate.

CT performance characteristics are specified by C57.13-1993 ANSI/IEEE standard [1]. This standard covers CT behavior under steady state and symmetrical fault conditions. Three documents published by the IEEE provide guidelines for the CT selection for different operating conditions including asymmetrical fault conditions [2-4]. Paper [5] presented additional approaches in the CT transient behavior estimation. However, when the protection system misoperation occurs or the CT behavior cannot be confidently estimated based on these documents, it is necessary to use other adequate modeling techniques. Comparison of different modeling techniques to model the CT V-I characteristics is presented in paper [6].

This paper presents simplified modeling techniques to model current transformers and power system areas involved in faults to study the impact on relay protection systems. To demonstrate the implementation and validity of suggested techniques, three cases of protection system misoperation are included in this paper: one event caused by multiratio main CT saturation and two events caused by auxiliary CT saturation. All simulations were performed using the ATP program.

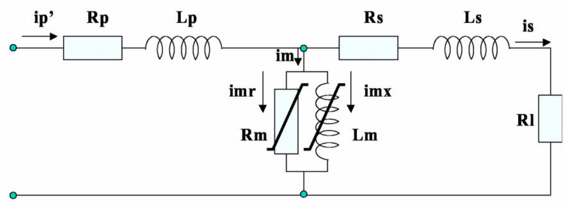
Multiratio CTs are designed with several taps so that appropriate ratio can be selected for a certain application. However, the CT C class is defined by the highest ratio. If used at different taps (reduced ratio), saturation voltage will be proportionally smaller than at the highest ratio which can impact the CT transient behavior. Many substations are fed by multiple lines to improve system reliability. These lines may be built at different times under different specifications so the same substation bus may utilize CTs with different turns ratios. When these CTs need to be connected to the same protective equipment, auxiliary CTs are widely used to match turns ratios. If the V-I characteristic of the auxiliary CT is not properly selected and does not match the characteristic of the main CT, the auxiliary or main CT can saturate and cause protection system misoperation [7-9]. Three cases and modeling techniques are presented in Section III.

The suggested techniques are also adequate to investigate the CT impact on protection in applications when CTs are properly sized but located far from the protection devices causing their saturation. The impact of CT saturation on protection device operation is different for different protection device types and protection schemes. Paper [5] investigated the influence of CT saturation on distribution system overcurrent protection when protection devices are located far from the CTs. A study was performed to verify that the CT saturation, reducing the secondary current RMS value, will not delay overcurrent protection response time to cause mis-coordination with other protection devices. The study confirmed that CT saturation will not significantly delay overcurrent protection operation for most common settings.

II. MODELING TECHNIQUES

A. Current Transformer Modeling

Current transformer (CT) equivalent circuit is shown in Figure 1.



Rp, Rs, Lp, Ls	-	primary and secondary winding resistance and leakage inductance
Lm	-	magnetizing inductance
imx	-	magnetizing current, reactive component
imr	-	magnetizing current, resistive component
Rl	-	CT burden including lead resistance
Rm	-	iron loss equivalent resistance

Figure 1. Current Transformer Equivalent Circuit

For the relay transient studies, the CT equivalent circuit of Figure 1 can be simplified as shown in Figure 2.

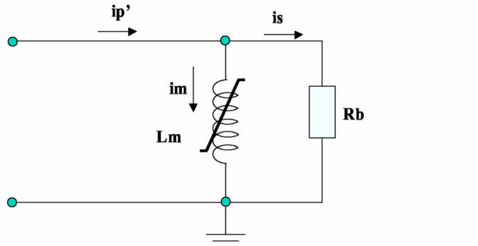


Figure 2. CT Modeling for the Relay Transient Studies

The magnetizing branch Lm is a non-linear element and can be determined from the CT V-I characteristic which is readily available. The Rb (Rb=Rs+Rl) value is also usually provided.

The magnetizing branch can be modeled on the CT primary or secondary. Modeling on the secondary is preferred because V-I curve measurements are regularly performed from the CT secondary. ATP CT models are based on the CT equivalent circuit and can be built using elements available in the program. The magnetizing branch is represented by nonlinear inductor elements whose nonlinear characteristics are specified in piecewise linear form by the user. Paper [6] presented a method to efficiently model the CT V-I characteristics. Since the flux-current data points are not readily available, ATP program provides a routine to convert the more commonly available V_{RMS}-I_{RMS} characteristics into an equivalent flux-current set. If a nonlinear inductance is externally added to a transformer model, the transformer model may be simplified by eliminating its magnetizing branch. It is also necessary to set the winding resistance in the transformer model to near zero, and add the winding resistance to the CT burden value. Hysteresis representation is not necessary in the most relay studies. However, remanence representation may be important. To include the effects of remanence on the CT performance, hysteresis can be modeled since remanence effects are easily studied with the hysteresis model. If the model cannot represent the hysteresis, it still may allow the specification of a steady state flux level at the beginning of a study to simulate remanence. Specification of an initial value of flux will simulate the presence of remanent flux as if the model had included hysteresis. Models that do not allow specification of initial value of flux and do not represent hysteresis are valid and produce satisfactory results for studies where remanent flux is not a concern. After the flux-current curve data has been included in the CT model, the model can be verified [5, 6].

B. Power System Modeling

Power system modeling can also be simplified when investigating only overcurrent effects on the relay protection system operation. Parameters for the fault simulations can include load currents, symmetric fault currents, source impedance, and power system time constant (or X/R) at the substation. A power system simplified model is shown in Figure 3. By changing the fault incidence angle, level of the fault current asymmetry (DC offset) can be controlled.

However, these simplified models are not adequate to study the impact of instrument transformers on protection system that use two input sources, voltage and current. Such studies require detailed modeling of power system components and wider area of power system representation.

The simplified models may not either be adequate to study special phenomena such as harmonics, ferroresonance, etc.

However, since the simplified models are easy to implement, they can be used to perform startup investigations of an event. If the results are not satisfactory, more detailed modeling techniques can be used. The results obtained by simplified methods will provide valuable directions how much to expand the modeling complexity.

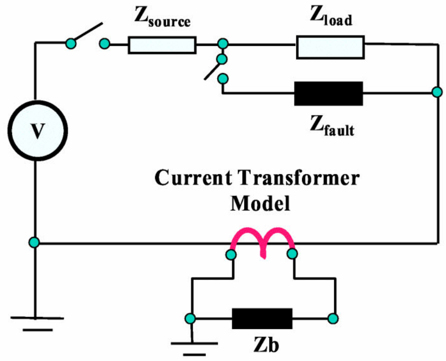


Figure 3. Simplified Power System Model

III. Test Cases

A. Multiratio Main CTs

Standards [1] specify multiratio CT behavior only for the highest ratio. However, the CT saturation voltage is proportionally smaller at smaller CT ratios, causing the CT to saturate at smaller fault currents. The following example shows the influence of multiratio CT saturation on a differential protection scheme [8]. The part of power system involved in the fault is show in Figure 4.

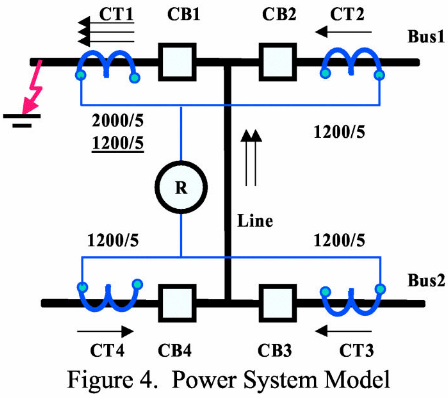


Figure 4. Power System Model

CTs at circuit breaker CB1 are multiratio 2000/5 A, C 800. Tap 1200/5 A was selected for the operation to match the ratio of CTs at circuit breakers CB2, CB3 and CB4 which were 1200/5 A, C 800. For a through-fault current relay should not operate since the total sum of currents seen by the relay will be near zero if the CTs do not saturate. In this case the relay operated due to CT1 saturation. The CT V-I curves are shown in Figure 5. The CT at CB1 with tap 1200/5 A has several hundred volts smaller saturation voltage compared to the CT2, CT3, and CT4.

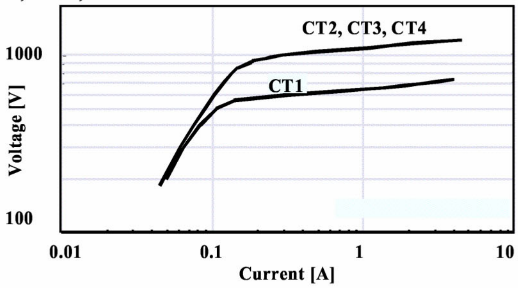


Figure 5. V-I Curves of CT1 and CT2

The current seen by the relay was distorted as shown in Figure 6, recorded by a digital fault recorder (DFR). The CT1 saturation was caused by the fault current contribution form three sides of the system passing through CT1. Computer simulations were performed by modeling CTs and the part of the power system involved in the fault as described in Section II. Figure 7 shows the simulated current waveform seen by the relay. A 40% remanence in the CT core was also represented to match the recorded waveform.

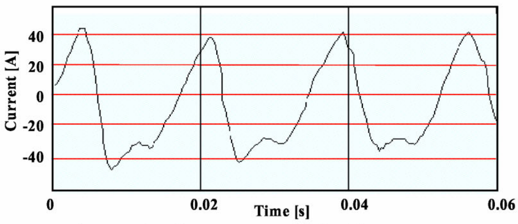


Figure 6. Current Recorded by DFR

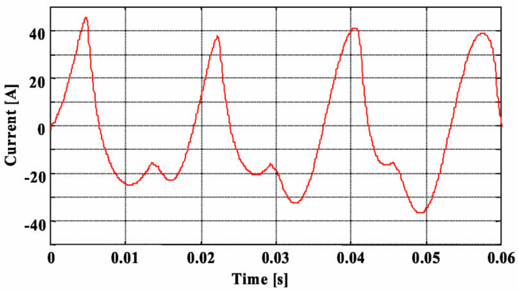


Figure 7. ATP Simulation of Current seen by DFR with Remanence in the CT Core

B. Multiratio Auxiliary CTs

The system model is shown in Figure 8. A single-phase-to-ground fault occurred at location "F". The fault was initiated by flashing-over due to icing and heavy rain at the CB3 disconnects, between phase C to ground, and then, after 20 ms, phase B flashed-over to ground, too [9].

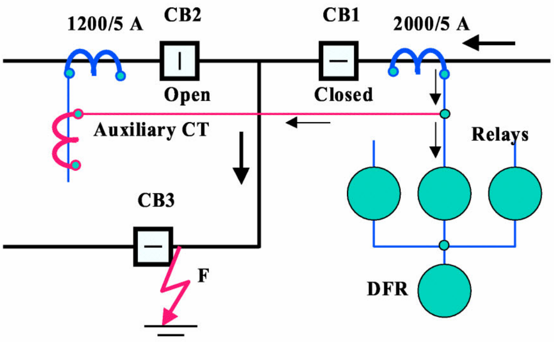


Figure 8. Power System Model

The CT ratio at CB1 was 2000/5A and at CB2 1200/5A. To match the CT ratios, 1.67/1 A auxiliary CTs were added. During the event, CB2 was open, while the auxiliary CT were connected to the 2000/5A CTs, as shown in Figure 8. Measured and simulated V-I curves for the main and auxiliary CTs are shown in Figure 9.

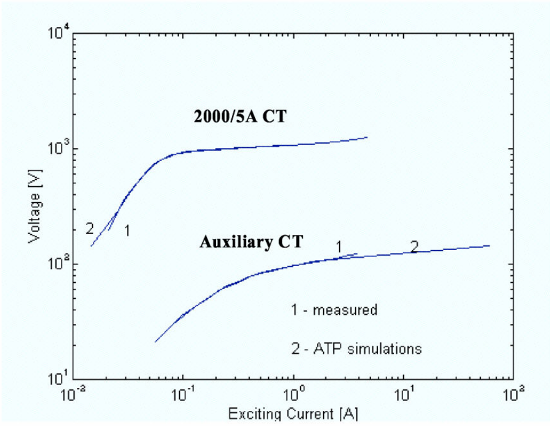


Figure 9. Measured and Simulated V-I Curves

Parameters for the fault simulations were based on the records and the fault study and included symmetric fault current 21 kA, time constant Tp=20 ms, fault incidence angle α=40°, and time delay between C phase to ground fault followed by B phase to ground fault 20 ms. The neutral fault current recorded by a DFR is shown in Figure 10. The simulated current waveform is shown in Figure 11.

The recorded current was distorted due to the auxiliary CT saturation, connected to the 2000/5 A CT secondary side while the 1200/5 A CT primary side was open. During normal operation auxiliary CT impedance is high seen by the 2000/5 A CT. However, when the 2000/5 A CT secondary voltage exceeded the auxiliary CT saturation level, the auxiliary CTs saturated, decreasing their impedance and diverting some currents through them instead through the relays.

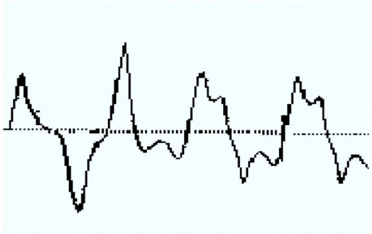


Figure 10. Recorded Current Waveform (C Phase-to-Ground Fault followed by B Phase-to-Ground Fault)

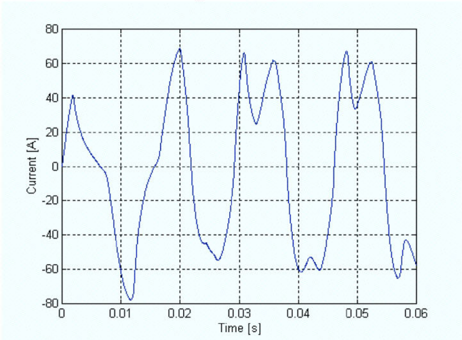


Figure 11. Simulated Current Waveform (C Phase-to-Ground Fault followed by B Phase-to-Ground Fault)

C. Differential Restricted Earth Fault Protection

During a three-phase fault in a substation (located at a large metropolitan utility) with five 138/28 kV transformers connected in parallel to the substation bus, restricted earth fault protection misoperated for all transformers causing a total power outage. The differential restricted earth fault protection scheme consisted of main and auxiliary current transformers (CTs) and one overcurrent relay in the differential branch. It was suspected that CT saturation caused the misoperation. To verify this hypothesis, a study was performed. Computer modeling included one power transformer and its associated restricted earth fault protection scheme. Three-phase and single-phase faults were simulated. The study results confirmed CT saturation as the cause for the misoperation.

To solve this problem, investigated solutions included upgrading the auxiliary CTs with higher saturation voltages and use of a resistor in the differential branch, since overcurrent relays cannot compensate for CT saturation errors. An alternative solution was the use of a multifunction relay with a true differential scheme providing inherent compensation for CT saturation error [10].

The study results and suggested solutions were verified by conducting the high power tests under real-life conditions. Sensitivity and stability of the scheme was tested. Sensitivity of the scheme included faults inside the protection zone and stability of the scheme faults outside the protection zone. Three-phase faults verified stability of the scheme and single-phase-to-ground faults verified both sensitivity of the scheme and stability of the scheme.

Figure 12 shows simplified single-line diagram of the restricted earth fault protection design representing one power transformer. Figures 13 and 14 show simplified computer models used to investigate the causes for the protection system misoperation. The system parameters were provided by the utility that included fault current levels and X/R at the substation.

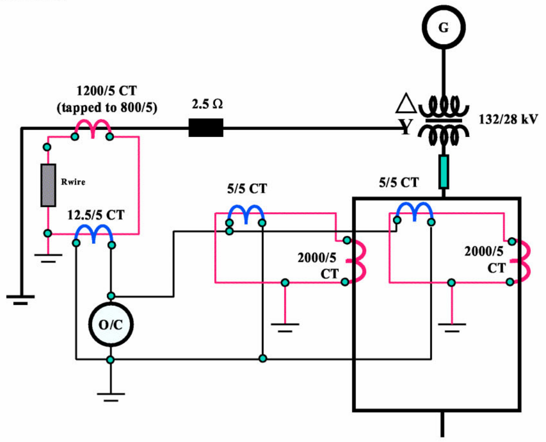


Figure 12. Simplified Single-Line Diagram of the Restricted Earth Fault Protection Design

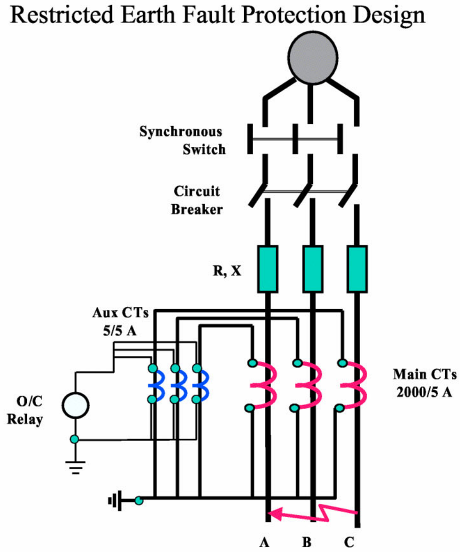


Figure 13. Power System Modeling to Study Three-Phase Faults (scheme stability)

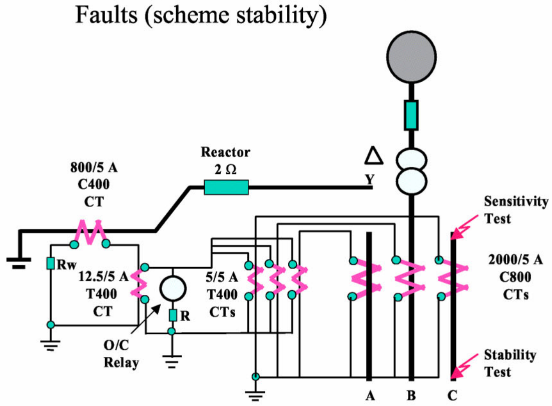


Figure 14. Power System Modeling to Study Single-Phase-to-Ground Faults (scheme stability and sensitivity)

Tested and simulated V-I curves for 2000/5 A, C800 main CTs are shown in Figure 15 and for 5/5 A, T400 and 12.5/5 A, T400 auxiliary CTs in Figure 16. Even though the CT V-I curves assumed in the study were different than the actual auxiliary CT V-I curves, laboratory tests confirmed the validity of the study results.

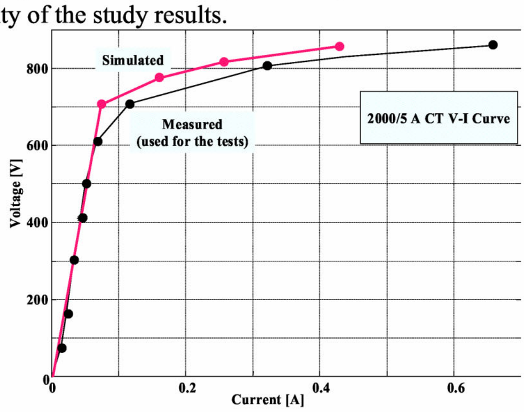


Figure 15. 2000/5 A Main CT V-I Characteristics

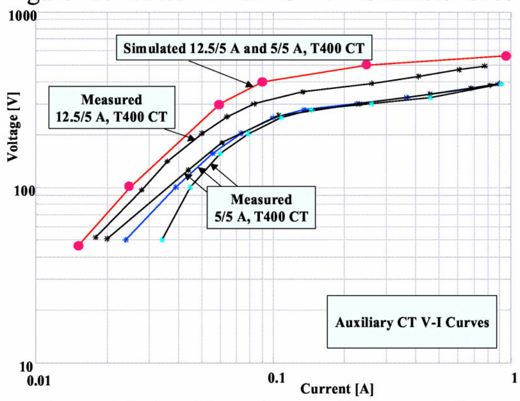


Figure 16. Auxiliary CT V-I Characteristics

Three-phase fault tests (stability) were performed using the scheme of Figure 13. At test current of 7.5 kA, representing actual conditions, relay did not operate. However, at 10 kA, the 2000/5 A CT saturated and caused differential current through the relay, causing its operation (Figure 17). After this test, the 2000/5 A CTs were demagnetized and the test repeated with 8 kA. During this test, the CTs did not significantly saturate and the relay did not operate.

These tests confirmed the study results that the T400 CTs have superior transient response over the existing CTs in place during the substation event. However, CT remanence can be a concern even with T400 auxiliary CTs during high fault current conditions.

Single-phase-to-ground fault stability tests were performed using the scheme of Figure 14. Faults were initiated outside the zone.

Three tests were performed with three different resistors connected in series with the O/C relay, R = 0, 2.5, and 5 Ω, to investigate their impact on relay operation. The resistor was used to de-sensitize the relay from operating during an external fault and to force a greater portion of the false residual current into the saturated CT's core. The test current was 3.4 kA asymmetrical, corresponding to the fault level in the substation. By adding resistors R = 2.5 and 5 Ω, the differential current peak value was reduced from 18 A (without resistor) to 12.6 A and 10 A respectively. The O/C relay did not operate.

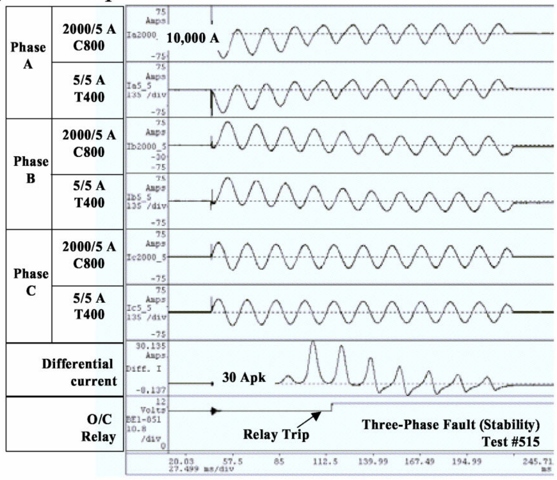


Figure 17. Three-Phase Fault (Stability, 10 kA Asymmetrical)

Single-phase-to-ground fault sensitivity tests were performed using the scheme of Figure 14. Faults were initiated inside the zone.

Three tests were performed using the same resistor values as in stability tests. The test current was 3.4 kA asymmetrical. Figure 18 shows test results with R = 2.5 Ω. The peak value of differential current through the relay was reduced from 20 A (without the resistor) to 18 A. Even though the neutral CT saturated, the relay operated within 23 ms. By adding resistor R = 5 Ω the peak value of differential current was reduced to 16.6 A resulting in delayed operation of the O/C relay, operated within 92 ms.

Figures 19 and 20 compare single-phase-to-ground fault sensitivity test results with computer simulations. The laboratory tests confirmed computer simulations to a high degree of precision.

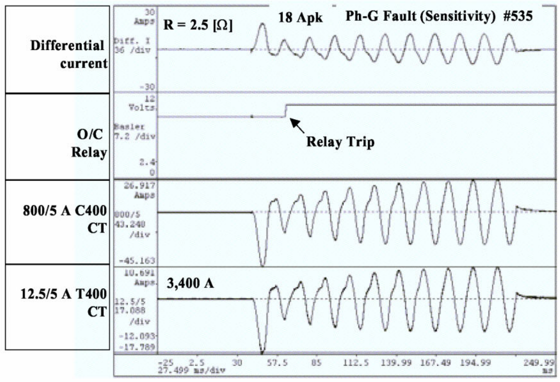


Figure 18. Single-Phase-to-Ground Fault (Sensitivity, R = 2.5 [Ω], 3.4 kA Asymmetrical)

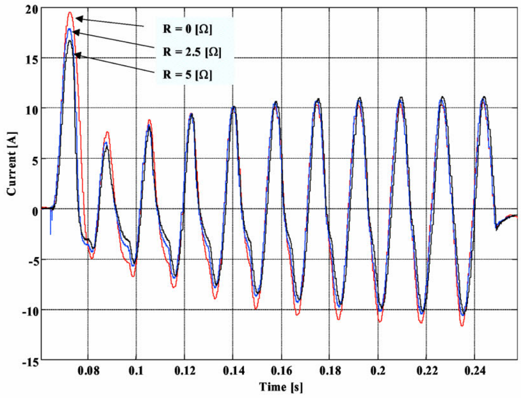


Figure 19. The Impact of adding Resistor in Series with O/C Relay on the Scheme Sensitivity (Single-Phase-to-Ground Fault, High Power Test)

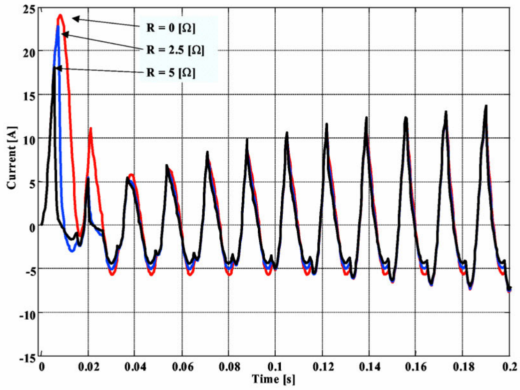


Figure 20. The Impact of adding Resistor in Series with O/C Relay on the Scheme Sensitivity (Single-Phase-to-Ground Fault, Computer Simulations)

The computer simulations were also performed assuming the neutral CT matched with phase 2000/5 A CTs and having higher C class that reduces its saturation. This replacement improves the CT transient response and obviates the need for the auxiliary neutral CT. However, this solution was more expensive than the resistor addition.

IV. Conclusions

This paper presents simplified modeling techniques to model current transformers and power system areas involved in faults that can be used for the relay protection transient studies.

The suggested techniques are easy to implement and provide good results. Three cases of protection system misoperation included in this paper confirm validity of the modeling techniques.

V. References

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VI. Biographies

Ljubomir A. Kojovic is a chief power systems engineer for Cooper Power Systems at the Thomas A. Edison Technical Center. He has a Ph.D. in power systems with specialties that include protective relaying, distributed generation, testing, digital modeling, and systems analysis. He is an adjunct assistant professor at Michigan Technological University. He is included on the roster of experts for the United Nations Development Organization (UNIDO) and is a registered professional engineer in Wisconsin. He is an IEEE Senior Member, member of the System Protection subcommittee, and member of several working groups of the IEEE Power System Relay Committee. He has earned four U.S. patents and authored more than 100 technical papers.