Field Experience with CT Saturation Due to Forced Current Redistribution

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***Abstract* - This paper describes field experience with protection misoperations caused by CT saturation subsequent to disturbance of CT secondary circuit connections. The increased excitation current associated with CT saturation allows the CT secondary currents to change in both magnitude and direction in order to accommodate the constraints of the circuit. By analyzing two system disturbance events described in this paper, the authors are able to use simple circuit analysis to explain why and how these changes occurred and to predict the new equilibrium state.**

***Keywords*: Field experience with CT saturation, CTs in series connection, Forced current re-distribution, Protection mis-operation, CT safety hazard.**

I. INTRODUCTION

CURRENT transformers (CTs) are common devices used in industry for metering and protective relaying purposes.

The theory and application of iron-core CTs has been mature for many years. A typical CT equivalent circuit and a CT excitation curve are shown in Figure 1. Figure 1 illustrates that the CT secondary voltage is a function of the excitation current. Below the knee-point of the excitation curve, the excitation current is relatively small, and is a complex combination of magnetizing, hysteresis, and eddy current components [1]. CT saturation occurs when the magnetizing flux exceeds the knee point on the excitation curve. When a CT saturates, the actual output current is subjected to large errors due to increased current flow through the excitation branch. There are many technical papers on the subject of modeling the behavior of CTs in the saturated region.

From a protection perspective, CT saturation will introduce significant discrepancy between primary current and expected secondary output currents. Both system disturbance events discussed in this paper are the result of protection mis-operations due to CT saturation.

Practically, there are three common scenarios in the field that can lead to CT saturation:

- a high magnitude of primary fault current;
- a fault current with high DC offset and long X/R time constant; or
- excessive burden in the CT secondary circuit.

However, two system disturbance events in the BC Hydro system have illustrated a scenario that can result in CT saturation, even in low-current and low relay and wiring burden conditions. In both events, the CT secondary currents were forced to re-distribute due to a disturbed wiring connection. When the circuits reached a new steady state, the CTs were operating in the saturation zone and the output currents had changed in both magnitude and angle. In both cases, the protection relays misoperated in response to the error in CT output currents.

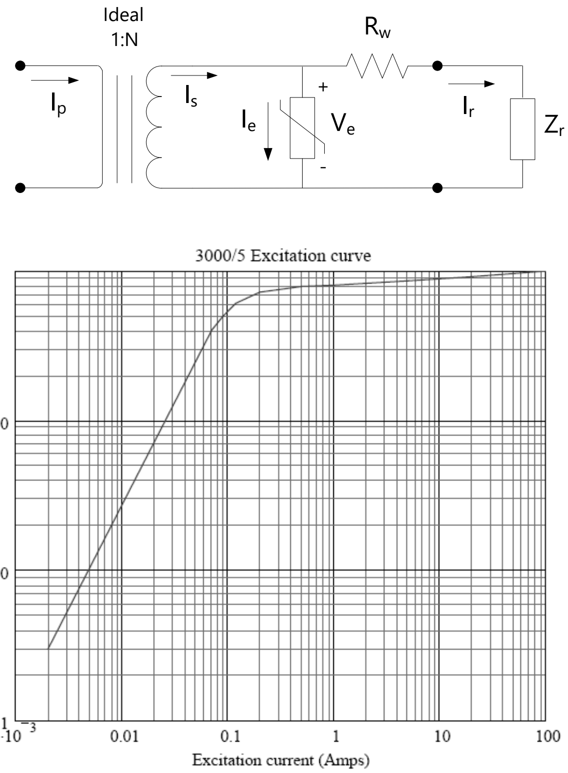

Fig. 1 Typical CT Equivalent Circuit and CT Excitation Curve

II. MISOPERATION EVENT I

A. General Description

This event occurred at BC Hydro's Nicola Substation (NIC) located in the south interior of BC. The circuit in discussion is a 138 kV line terminal (1L243) at NIC. A simplified one line diagram is shown in Figure 2. In normal operation, 1CB17 carries the majority of 1L243 current while breaker 1CB18 only carries minimal current since the two line currents are relatively equal.

The line protection consists of two sets of identical protection equipment, such as relays, CTs, and VT. In this paper, only primary protection is relevant to the discussion. Therefore, Figure 2 only shows the primary protection (21L) connection on NIC 1L243 terminal.

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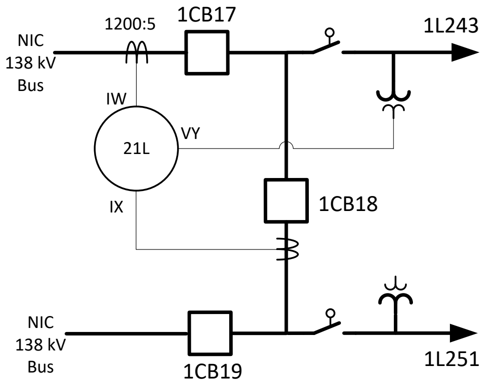


Fig. 2 Simplified 1L243 Protection One line Diagram

B. *Event Analysis*

The event started when a field staffer heard a faint arcing noise when he was applying cable ties around wire bundles in the 1CB17 cubicle. The source of arcing noise was narrowed down to a small terminal block area when 1L243 tripped. No auto-reclose was attempted after the trip.

The target was found to be B-G fault on the primary relay (21L), however no event record was triggered on the standby relay (21LS). A review of the primary relay event record shows that line voltages were healthy; but currents in B and C phase were atypical, almost 180 degrees out of phase. Figure 3 is the event record showing the line voltage and current waveforms. The primary protection relay detected an intermittent residual over-current (3I0) and triggered a series of event records until it finally timed out and issued a non-reclosable trip.

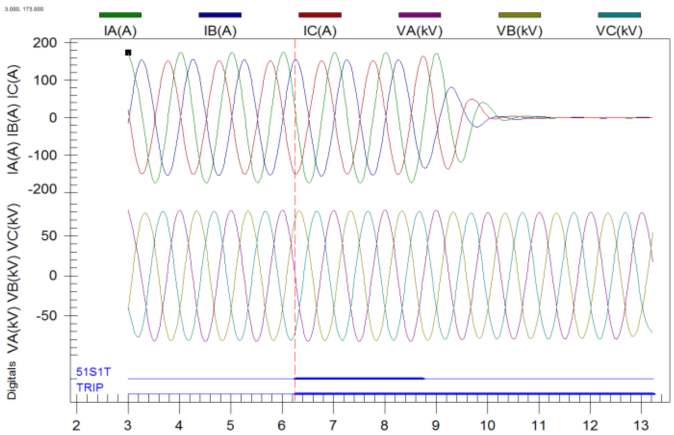


Fig. 3 1L243 Event Record

Further review of the COMTRADE event record (which shows both CT inputs separately) revealed the source of disturbed current reading was from the 1CB17 CT, while 1CB18 CT currents remained small but balanced. 1CB17 was taken out of service for inspection. Later, it was reported that one loose connection was found in the 1CB17-CT1 neutral connection.

Figure 4 is a simplified wiring diagram for the 1CB17-CT1 connection. The CT was Wye-connected. Referring to Figure 4 below, the loose connection was found at 6X3 which is the neutral connection between C phase and A phase CTs. This disconnection effectively separated the Wye-connected three phase CT circuit into two separate circuits. The A phase CT was connected normally to the relay and neutral, however, B and C phase CTs were in series without a connection to the neutral. Basic circuit analysis shows that the only solution is for I_b and I_c at the relay to be of equal magnitude and opposite direction.

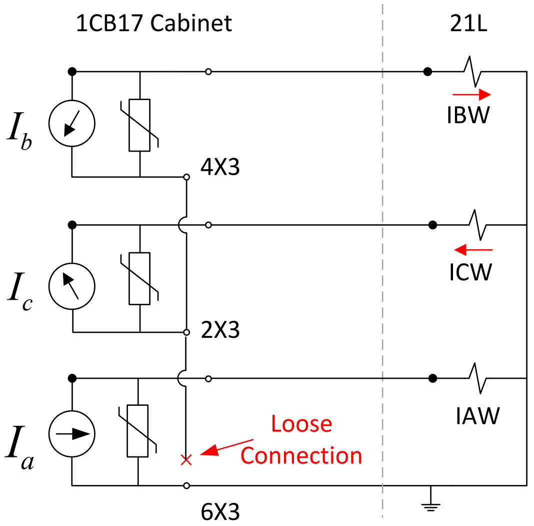
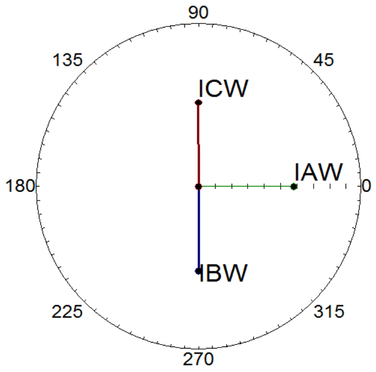


Fig. 4 Simplified 1CB17 CT Connection Diagram

C. *CT Saturation Analysis*

The root cause of the protection mis-operation was simple. However, it is interesting to a protection engineer that currents on B and C phase not only shifted in angle to become opposite in direction, but also reduced in magnitude to approximately 87% of their original value, as shown in Figure 5. How did it reach the new steady state?



$$I_{BW} = -I_{CW}$$
$$|I_{BW}| = 0.87|I_{AW}|$$

Fig. 5 Phasor Diagram of 1CB17 CT Currents after Re-distribution

For a CT circuit, the primary current will flow regardless of the status of the secondary connections. However, if the topology of the secondary circuit constrains the secondary current such that it does not equal the primary current divided by the CT ratio, the magnetizing branch of the CT will absorb currents to allow the constraint to be met (aka CT saturation). Another way to describe it is that the CT has to saturate to allow the secondary output current to change until the circuit is balanced. However, there are an infinite number of ways to meet the constraint $I_b = -I_c$, why did it settle down as is?

The answer comes from applying basic circuit analysis theory. If we redraw the circuit as in Figure 6, we can determine by inspection that $I_b' = -I_c'$.

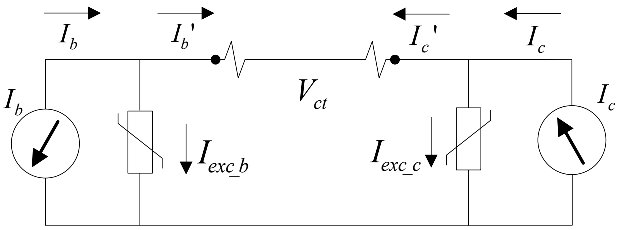


Fig. 6 Event #I CT Secondary Circuit

If we make the further assumption that the wire and relay burden between the two excitation circuits is small with respect to the impedance of the magnetizing branches[1], then we can make a further simplification of the equivalent circuit and state that the terminal voltage V_{ct} for both CTs is identical, meaning that if the CTs have identical excitation characteristics, the excitation current in both CTs must be identical, i.e. $I_{exc\_b} = I_{exc\_c}$. Further algebraic simplification results in the solution below.

$$\begin{cases} I_b' = I_b - I_{exc\_b} = -(I_c - I_{exc\_x}) = -I_c' \\ I_{exc\_b} = I_{exc\_c} = I_{ex} \end{cases}$$

$$I_b - I_{ex} = -(I_c - I_{ex})$$

$$I_b + I_c - 2I_{ex} = 0$$

$$\therefore \begin{cases} I_{ex} = \dfrac{(I_b + I_c)}{2} \\ I_b' = \dfrac{I_b - I_c}{2} \\ I_c' = \dfrac{I_c - I_b}{2} \end{cases}$$

As shown in Figure 7, the excitation current required to reach the new balance state causes a 30 degree shift each way and forms a right-angled triangle. The red arrow indicates the excitation current. A simple calculation proves that the new steady state current is equal to cos (30°) or 87% of the original magnitude. This mathematically confirms the phasor relationship observed from the event record (Figure 5).

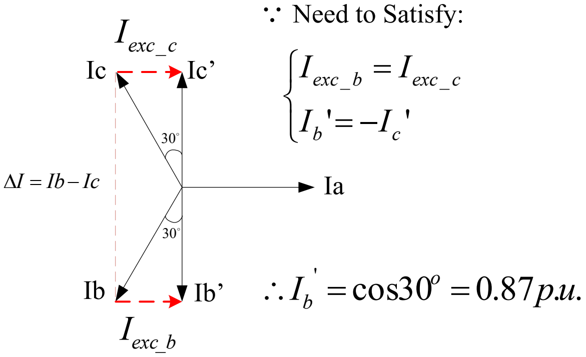


Fig. 7 Excitation current aligns current phasors

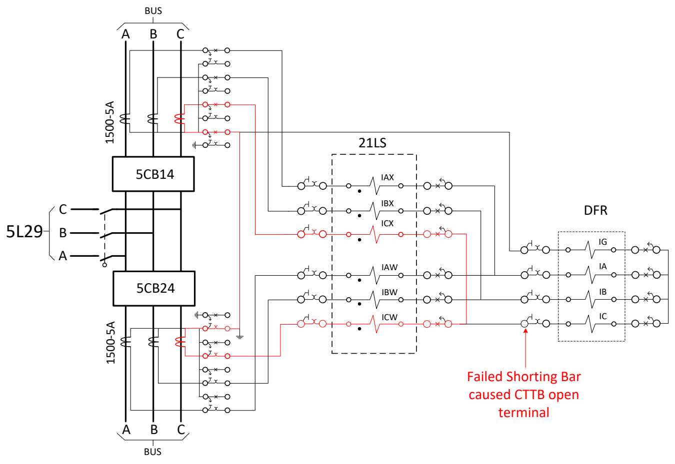
It is noted that because the primary system is well balanced, the current angle shift for both CTs is identical at 30 degrees. If the pre-disturbance condition currents were not perfectly matched, the angle change would be different, as will be seen in the next event.

III. MISOPERATION EVENT II

A. General Description

The circuit in discussion is a 500 kV transmission line terminal (5L29) in BC Hydro's Dunsmuir (DMR) substation. 5L29 line protection utilizes redundant digital protection relays. The protection scheme is typical step impedance and directional over-current protection with the communication aided permissive over-reaching transfer trip (POTT). 5L29 also features a single pole tripping and reclosing scheme (SPTR) to maintain power transfer during single phase trips to aid secondary arc extinction [2] [3]. In this particular line, the single phase open pole interval is set to 68 cycles.

A simplified three phase wiring diagram is shown in Figure 8 to illustrate the bushing CT connections to the line protection relay (21LS). It is worth noting that the CTs are connected individually through the relay first before being combined at a Digital Fault recorder (DFR) to record the total line current. For each device, there is a standard CT Test Block (CTTB) to provide shorting and isolating functionality.



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[1] This is a good approximation when CTs are not heavily saturated, as the impedance of the magnetizing branch is near infinite under normal operation and drops as the CT saturates.

Fig. 8 Simplified Three Line CT Connection Diagram

B. *Event Analysis*

In February 2014, 5L29 was forced out of service after a series of protection operation events. The event started with a single phase trip followed by an automatic reclose. The auto reclose failed and forced both terminals to trip three phases.

The first step of investigation revealed there was probably no fault on the line. The primary protection relay (21L) event record showed that line voltages and currents were normal prior to the trip. The protection operation was only initialized from the standby protection relay (21LS). Its event record showed C phase current was net zero in total. The unbalance current readings triggered the permissive trip scheme and eventually activated the trip outputs when the permissive trip was echoed back from the remote terminal. The auto reclose failed since the standby relay continued to see the “fault” after the line reclosed.

Further investigation analyzed the C phase current from both circuit breakers – 5CB14 and 5CB24. As shown in Figure 9, both breaker CT C phase currents had a step change in magnitude, and the phase angles shifted to become opposite to each other. This effectively resulted in net zero total current and led to the protection mis-operation.

It was later reported that a failed shorting bar was found at the DFR CTTB, as shown in Figure 8 above. When the field crew was performing routine maintenance on the DFR, the shorting bar opened rather than shorting to neutral. Hence, the two originally parallel connected CTs formed a series circuit. The currents flowing through ICX and ICW in 21LS relay became equal magnitude and opposite direction, as shown in Figure 9. This explains why the total C phase line current seen by the relay was nearly zero in the event record.

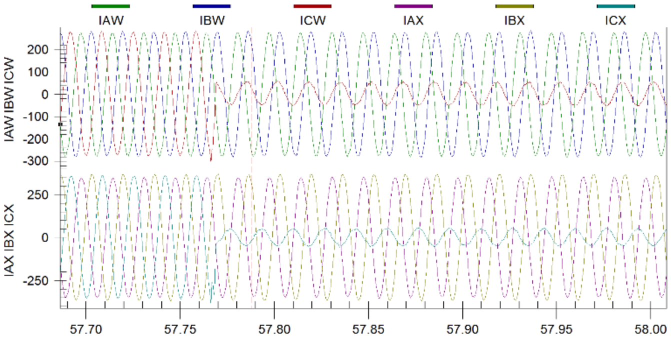


Fig. 9 Event Record Showing Equal and Opposite C Phase Currents

C. *CT Saturation Analysis*

Two main questions arose during the event analysis:

Q1: Similar to Event I above, the originally paralleled CT circuits became series connected. But the behavior of the relay currents was quite different. In Event I, the magnitude of currents reduced to 87% after the disturbance, but in this event, the post-disturbance currents were much smaller, only 16% or less of the original magnitude. In addition, both currents show unequal phase shifts. As can be seen in Figure 10, ICW’s angle shifted more than ICX’s. Given that these two CTs are of same type, why would they behave differently?

Q2: The post-disturbance C phase current waveforms are relatively clean and remain sinusoidal, as shown in figure 9 and 13. How did the CTs maintain sinusoidal outputs when they were heavily saturated?

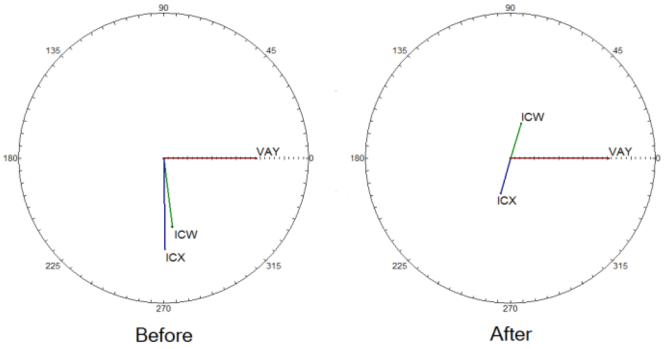


Fig. 10 Current Phasors Before and After the Disturbance (not to scale)

The equivalent schematic for this event is essentially identical to that of event #I, with only changes to source CT current directions and labels.

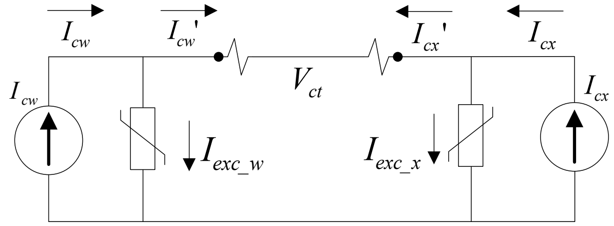


Fig. 11 Event #II CT Secondary Circuit

Again, this reduces to the same system of algebraic equations we derived for Event I, with the same solution.

$$\therefore \begin{cases} I_{ex} = \dfrac{(I_{cw}+I_{cx})}{2} & (1) \\ I_{cw}' = \dfrac{I_{cw}-I_{cx}}{2} & (2) \\ I_{cx}' = \dfrac{I_{cx}-I_{cw}}{2} & (3) \end{cases}$$

For verification, the pre-disturbance data from the event record was plugged into the above equations and theoretical post-disturbance values were calculated.

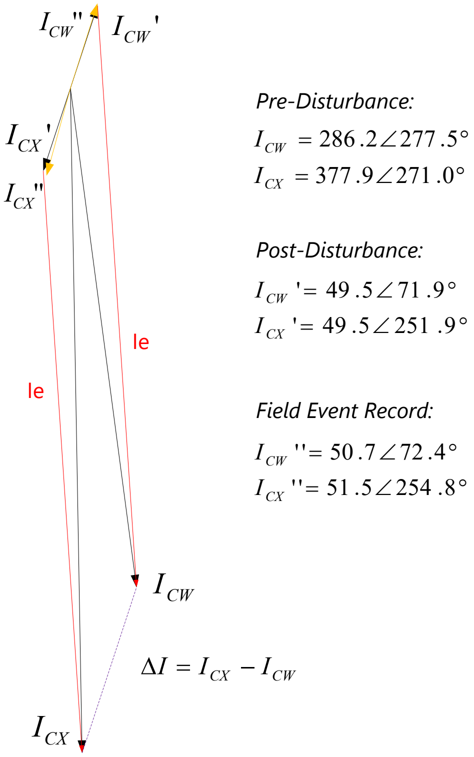
Pre-disturbance data:

$$\begin{cases} I_{cw} = 286.2\angle 227.5^{o}\,A \\ I_{cx} = 377.9\angle 271^{o}\,A \end{cases}$$

Post-Disturbance calculation results:

$$\begin{cases} I_{ex} = 331\angle -86^{o}\,A \\ I_{cw}' = 49.5\angle 71.89^{o}\,A \\ I_{cx}' = 49.5\angle 251.89^{o}\,A \end{cases}$$

The algebraic solution is plotted in Figure 12, together with the field record values. It clearly shows that the calculated results match the field record. It is noted that the field record is in unfiltered format. The discrepancy may vary at different sampling points, but in general the field record values are within +/- 10% of the calculated value.



Pre-Disturbance:

$I_{CW} = 286.2\angle 277.5°$

$I_{CX} = 377.9\angle 271.0°$

Post-Disturbance:

$I_{CW}' = 49.5\angle 71.9°$

$I_{CX}' = 49.5\angle 251.9°$

Field Event Record:

$I_{CW}'' = 50.7\angle 72.4°$

$I_{CX}'' = 51.5\angle 254.8°$

Fig. 12 Theoretical Values vs. Event Record Data

It is also interesting to note that the excitation current associated with the 5CB24 CT (I_{CW}) exceeds the pre-disturbance current from the CT in Figure 12. Referring to equation (1), since each CT shares half of the **total** excitation current, it is entirely possible that the excitation current in the CT exceeds the pre-disturbance current.

We can now consider another scenario: what will happen if the pre-disturbance condition is perfectly balanced, i.e. I_{CW} and I_{CX} are identical and $\Delta I=0$? According to equations (2) and (3), the balance point for the new circuit will be at zero. All current will be absorbed in the CTs' excitation branches and no current will be seen by the protection relay.

Question 2 in the beginning of this section can be addressed by Equation (1), (2), and (3). Since the relay output current (I_{CW}' or I_{CX}') is proportional to the difference in the unsaturated CT currents (I_{CW} and I_{CX}), the relay output current will remain sinusoidal even though the CTs are saturating. In addition, the CT excitation current must also remain sinusoidal to satisfy the equations. This will remain true as long as the two CTs have identical excitation characteristics and the voltage drop corresponding to wire and relay burden is minimal with respect to the excitation voltage of the CTs. Figure 13 is a high resolution (2000 samples/sec) event record and the relay current associated with the saturated CTs shows no visible signs of what we typically consider CT saturation. This is a non-intuitive result for protection engineers accustomed to seeing textbook CT saturation current waveforms.

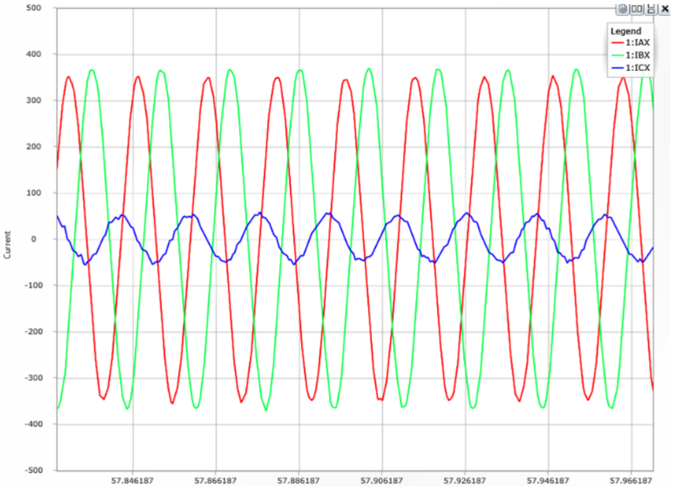


Fig. 13 Atypical Sinusoidal CT Saturation Current Waveform

IV. NUMERICAL ANALYSIS

While the preceding analysis is very efficient, as it only requires simple algebra, the results appear to defy intuition that saturated CT current waveforms can be sinusoidal. Because of this and concern about certain approximations and assumptions taken in the algebraic analysis, a numerical simulation was performed of a system with two interconnected CTs, connected to different phases of the AC system, both to verify the previous results and see if any additional insight could be gained.

The system was modeled using Analog Devices LTSpice XVII software. While EMTP or one of its variants would typically be the first tool considered for this task, the reality is that the basic algorithms behind all time domain circuit analysis software are quite similar, and while EMTP and its variants have definite advantages when modeling three phase power systems with transmission lines, sometimes "the tool you have is more useful than the tool you don't have". The first task was to model a generic 3000:5 C800 CT. The CT is modeled as a pair of coupled inductors with an inductance ratio of $1:600^2$, with a parallel magnetizing branch modeled using the Chan model[4], which is natively supported by LTSpice. Secondary winding resistance of 1 ohm is added. In order to verify the excitation characteristic of this simulated CT, the primary winding is left open circuited, while the secondary is driven by a 60 Hz voltage source that ramps from 0 – 1000 V rms. The 1 cycle window RMS excitation voltage and excitation current are then calculated using behavioural sources, which are then plotted on a log-log X-Y plot to produce the excitation curve. The air gap on the core is kept minimal to emulate a TPS/TPX style CT. Figure 14 shows the excitation curve of this simulated CT during artificial excitation testing.

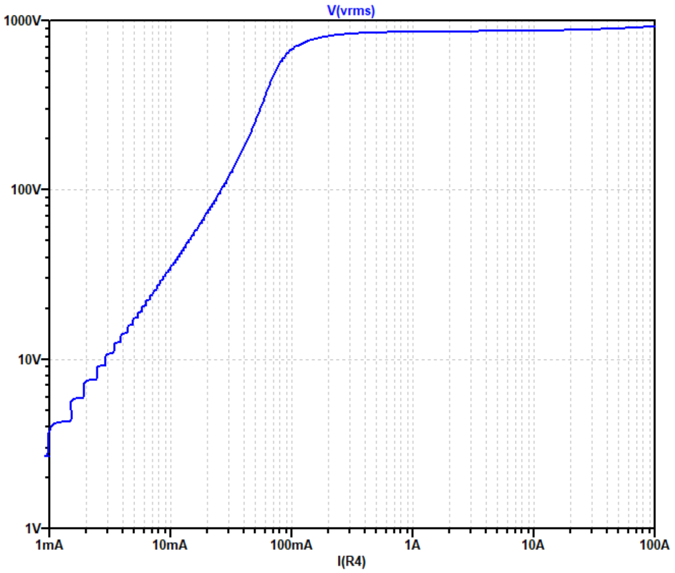


Fig. 14 Excitation curve of example CT

We then take two of these CTs and connect their primaries to different AC current sources, then interconnect the secondaries in a manner consistent with the events listed earlier in the paper. This allows us to simulate the events previously analyzed. In the first simulation, we simulate the first event, where B and C phase CTs ended up in series due to a failed neutral connection. In the pre-contingency timeframe (0 – 50 ms), we see the normal phase relationship between the B and C phase secondary currents, but once the neutral connection for B and C phase is opened, the B and C phase secondary currents are forced to be equal and opposite, as noted in section IIc. The secondary current magnitudes drop from 624 mA to 540 mA (87%) and the angles change from 120 degrees to 180 degrees.

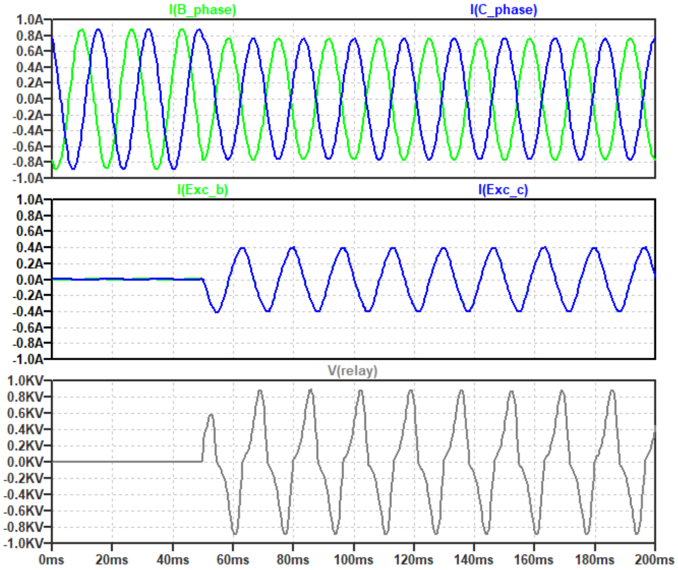


Fig. 15 B and C phase CTs interconnected

The excitation currents of both CTs are identical and sinusoidal, and the excitation voltage becomes non-linear in order to maintain the sinusoidal current in the excitation circuits.

Running another simulation closer to the second event, with the pre-fault currents in phase, but with different magnitudes, we get the same result as our manual method, with each CT producing the difference between the two pre-fault currents.

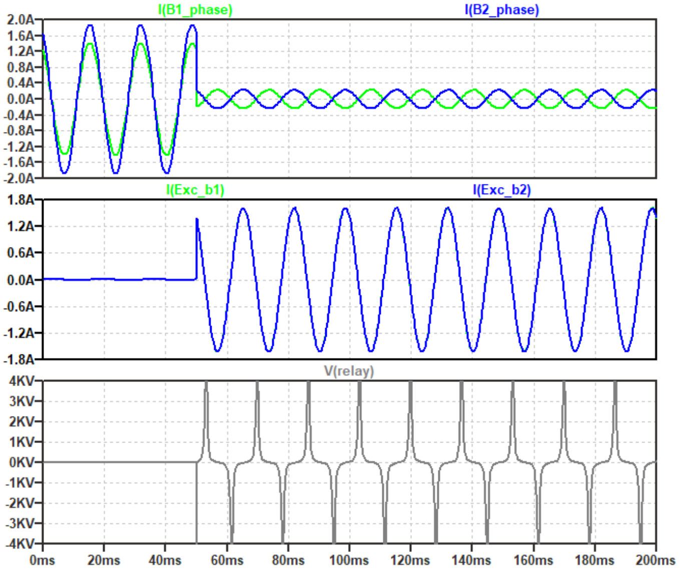


Fig. 16 Two B phase CTs interconnected

Finally, to gain more insight into the limits of our simplistic circuit analysis, the first simulation was rerun, but with higher currents (3000 A pri) and a core area reduced by a factor of 10 to make our C800 CT not quite a C100.

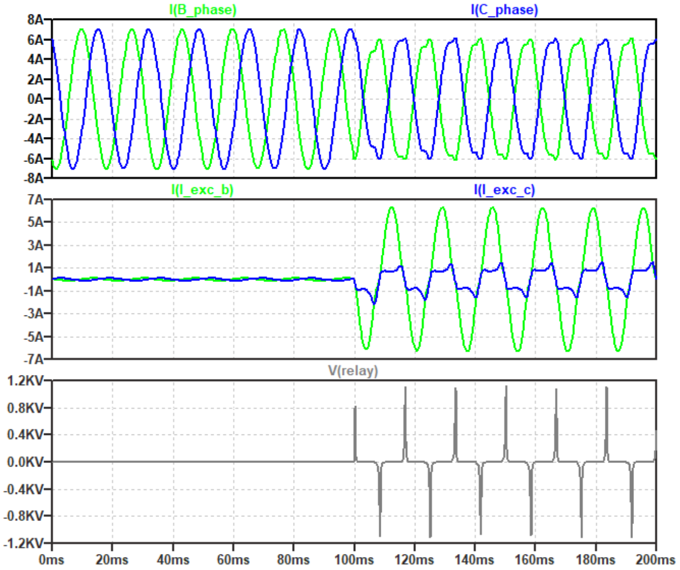


Fig. 17 B and C phase CTs interconnected – extreme edition

In this simulation, while the two relays currents still drop by a factor of approx. 87% when they are placed in series, we see that the two CTs' excitation currents no longer match, and that the relay current is no longer sinusoidal. This can be explained by a few factors.

First, at the moment at which the two CTs are connected in series, they are each at a different point in their B-H curve, so one will saturate before the other, even though they have nearly the same voltage applied to them. When this happens, due to the much lower slope of the B-H curve at saturation, the saturated CT will absorb nearly all the required excitation current. In this simulation, the B phase CT reaches saturation first and takes more of the excitation current.

Secondly, as the currents in the CT secondary circuit increases, the voltage drop across the wiring also rises. Again, due to the nearly horizontal slope of the B-H curve as we move deeper into saturation, the current splitting between the two cores is very sensitive to minor changes in CT voltage (or CT saturation voltage). While this fairly extreme example shows the limitations in the simplistic algebraic method shown in the first part of the paper, it also shows that these are not major limitations. The excitation current in the two CTs may not be exactly equal, and the currents may not be exactly sinusoidal, but the resulting currents in the two relaying circuits are approximated well enough for most protection purposes using the simplistic algebraic model.

V. CONCLUSION

Connecting CTs which are carrying different primary currents in series will result in CT saturation. The increased excitation current associated with CT saturation allows the CT secondary currents to change in both magnitude and direction in order to accommodate the constraints of the circuit. By analyzing two system disturbance events described in this paper, the authors are able to use simple circuit analysis to explain why and how these changes occurred and to predict the new equilibrium state.

Finally, even though the current waveforms remained sinusoidal, the CTs were still being forced into saturation, with the high CT terminal voltages that accompany saturation. We were fortunate in both events that the safety issue was discovered quickly, and that the voltage on the CT wiring (estimated around 300V in an EMTP study [5]) did not damage the equipment or result in worker safety incidents.

VI. REFERENCES

[1] IEEE PSRC Committee C37.110 “IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes” https://ieeexplore.ieee.org/document/4483716

[2] IEEE Committee Report, “Single phase tripping and auto reclosing of transmission lines*”, IEEE Trans Power Delivery*, Vol. 7 Issue 1, p.p. 182-192 , January 1992 https://ieeexplore.ieee.org/document/108906

[3] M. Nagpal, S. Manuel, B. E. Bell, R.P. Barone, C.F. Henville, D. Ghangass, “Field Verification of Secondary Arc Extinction Logic”, *IEEE Trans. Power Delivery*, Vol. 31, No. 4, August 2016, p.p. 1864-1872 https://ieeexplore.ieee.org/document/7279164

[4] J. H. Chan, A. Vladimirescu, X. C. Gao, P. Liebmann and J. Valainis, "Nonlinear transformer model for circuit simulation," in IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, vol. 10, no. 4, pp. 476-482, April 1991, doi: 10.1109/43.75630. https://ieeexplore.ieee.org/document/75630

[5] S. Manuel, “Differential Open Circuited CTs Causing a Voltage Safety Hazard with 5L29 as an Example”, May, 2014

VII. BIOGRAPHY

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