

Field Experience with CT Saturation Due To Forced Current Re-distribution

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Abstract - This paper describes field experience with protection mis-operations 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 recent 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 direction. In both cases, the protection relays mis-operated in response to the error in CT output currents.

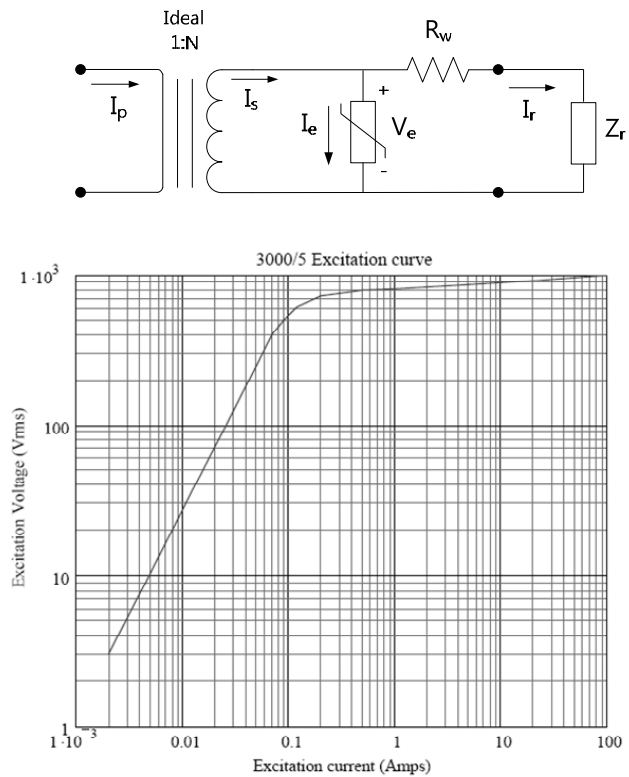


Fig. 1 Typical CT Equivalent Circuit and CT Excitation Curve

II. MIS-OPERATION 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)

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connection on NIC 1L243 terminal.

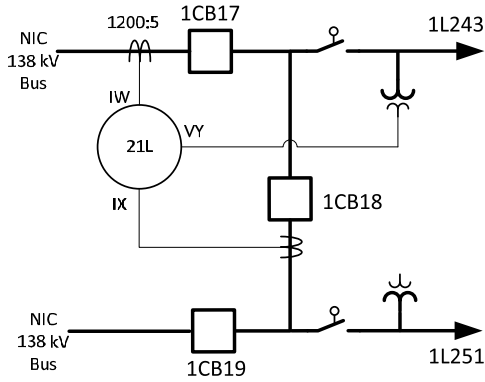


Fig. 2 Simplified 1L243 Protection One line Diagram

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.

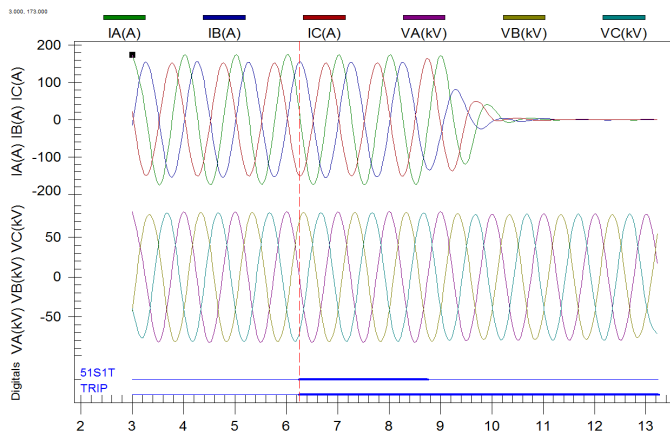


Fig. 3 1L243 Event Record

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.

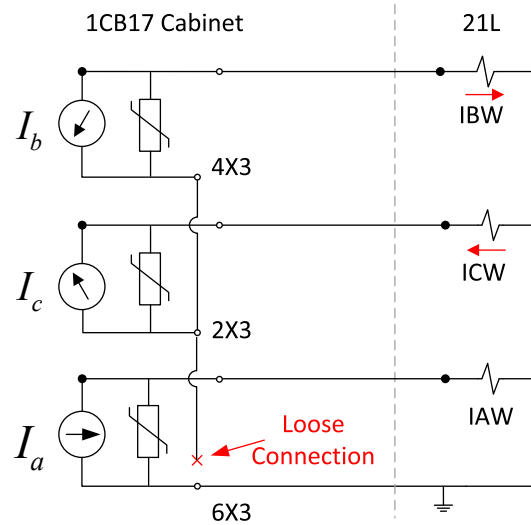


Fig. 4 Simplified 1CB17 CT Connection Diagram

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?

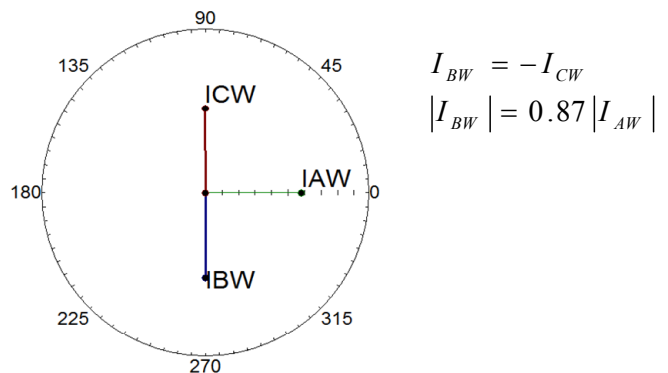


Fig. 5 Phasor Diagram of 1CB17 CT Currents after Re-distribution

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 $I_b' = -I_c'$.

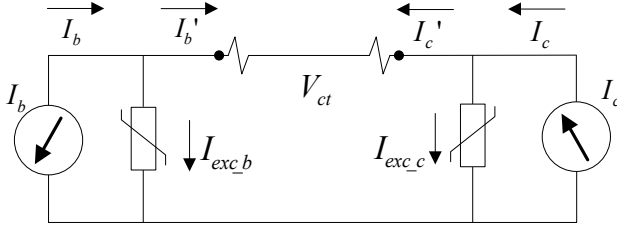


Fig. 6 Event #1 CT Secondary Circuit

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 branches¹, 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.

$$\begin{cases} I_b' = I_b - I_{exc_b} = -(I_c - I_{exc_c}) = -I_c' \\ I_{exc_b} = I_{exc_c} = I_{ex} \\ I_b - I_{ex} = -(I_c - I_{ex}) \\ I_b + I_c - 2I_{ex} = 0 \end{cases}$$

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

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 $\cos(30^\circ)$ or 87% of the original magnitude. This mathematically confirms the phasor

relationship observed from the event record (Figure 5).

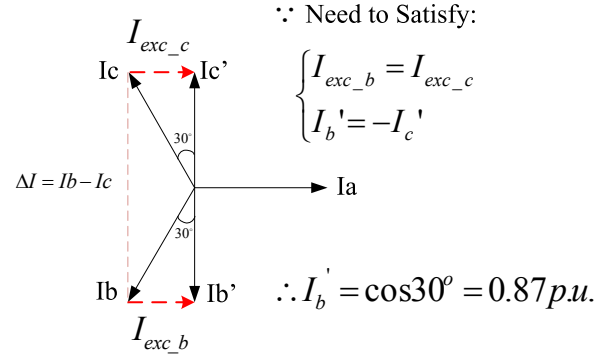


Fig. 7 Excitation current aligns current phasors

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. MIS-OPERATION 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.

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.

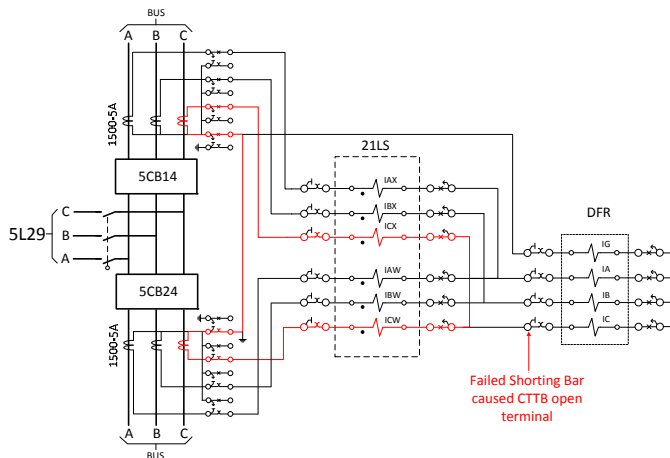


Fig. 8 Simplified Three Line CT Connection Diagram

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.

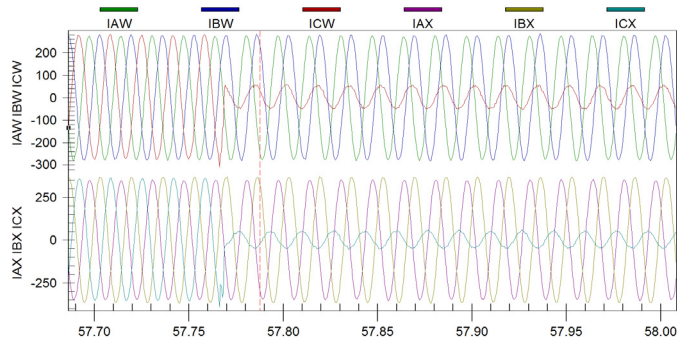


Fig. 9 Event Record Showing Equal and Opposite C Phase Currents

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?

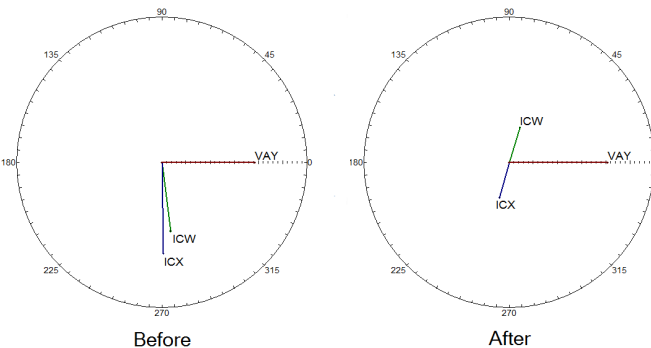


Fig. 10 Current Phasors Before and After the Disturbance (not to scale)

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

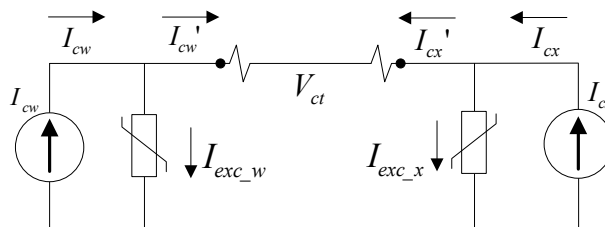


Fig. 11 Event #II CT Secondary Circuit

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

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

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:

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

Post-Disturbance calculation results:

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

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.

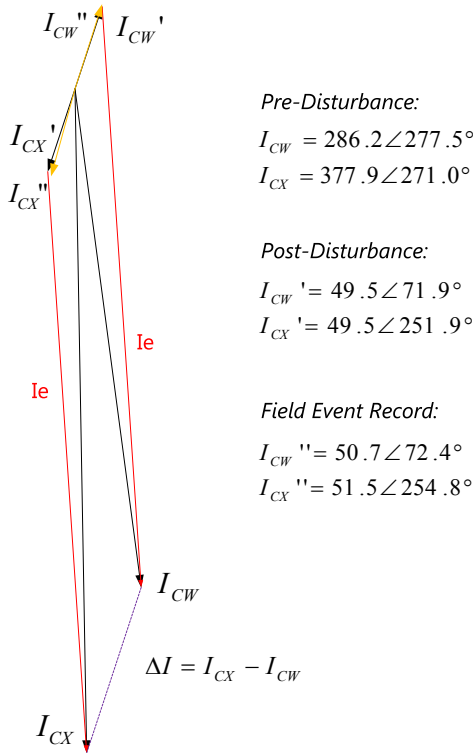


Fig. 12 Theoretical Values vs. Event Record Data

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.

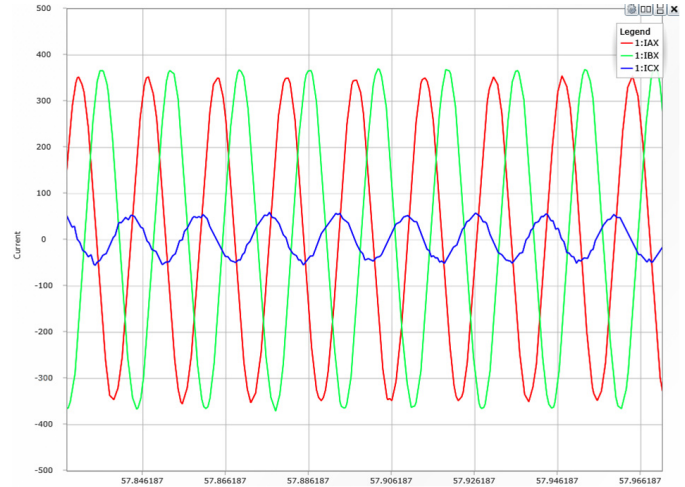


Fig. 13 Atypical Sinusoidal CT Saturation Current Waveform

IV. 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 [4]) did not damage the equipment or result in worker safety incidents.

V. REFERENCES

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VI. BIOGRAPHY



Hongbo Apollo Zhang is a registered Professional Engineer in the province of B.C. He joined BC Hydro in 2005 and was a Senior Engineer in the Protection and Control Support Service group when this paper was drafted. He is currently BC Hydro’s P&C Team Lead on the Site C Clan Energy Project (a 6-unit, Greenfield Hydroelectric project). Apollo holds an M. Eng. degree in Electrical Engineering from the University of British Columbia (UBC) and a B.A.Sc. degree from Fuzhou University (Fuzhou, China).



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