Mitigation of Voltage Drop Using Pre-Insertion Resistor during Large Transformer Energization in a Weak System: Simulation and Field Verification

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Abstract-- **Significant voltage drops can be expected during the energization of a large transformer in a weak system due to high inrush currents. Although controlled switching techniques are now available, pre-insertion resistors continue to be applied control the inrush current and mitigate the large voltage depression[1][2][3]. One of the factors that leads users to apply closing resistors is the concern that the accuracy in timing of breaker opening and closing in controlled switching may not be achievable, especially where there is a large variation in ambient temperature range. There is a perception that timing is less critical in application of closing resistors compared with controlled switching.**

This paper presents the results of a PSCAD/EMTDC study to confirm the selection of a suitable pre-insertion resistor and minimum insertion time for a 230 kV breaker which would be used to energize a 230kV phase shifting transformer and 230/345 kV auto-transformer at a 115/230/345 kV substation. A comparison has been made between the simulated results and field fault recorder traces for several energization events. The simulation results demonstrate good agreement with the actual energization behavior.

The results indicate that breaker timing, especially the duration of insertion time, is also a factor in the application of closing resistors. Insertion time is a very important parameter which affects the effectiveness of a closing resistor solution. Variations in breaker timing which reduce the total insertion time of the closing resistor can reduce the effectiveness of closing resistors in this application.

Keywords: **Transformer Inrush, Pre-insertion Resistor, Insertion time, PSCAD/EMTDC Simulation.**

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I. Introduction

Minnesota Power (MP) in conjunction with American Transmission Company (ATC) has replaced an existing phase shifting transformer bypass breaker (8TX) with a new breaker equipped with pre-insertion resistors at a 230/345 kV substation as shown in Fig. 1. The closing resistors are intended to mitigate the voltage depression on the adjacent power system due to transformer energization inrush currents that could occur during the energization of either Phase Shifting Transformer (PST) or 230/345 kV Autotransformer (T3). Very severe transient voltage drop can be expected during energization of the 230 kV phase shifting transformer and 230/345 kV autotransformer (both 800 MVA) since the system short circuit strength can be very low at this substation especially under line outage conditions. The short circuit MVA with all lines connected is 3600 MVA.

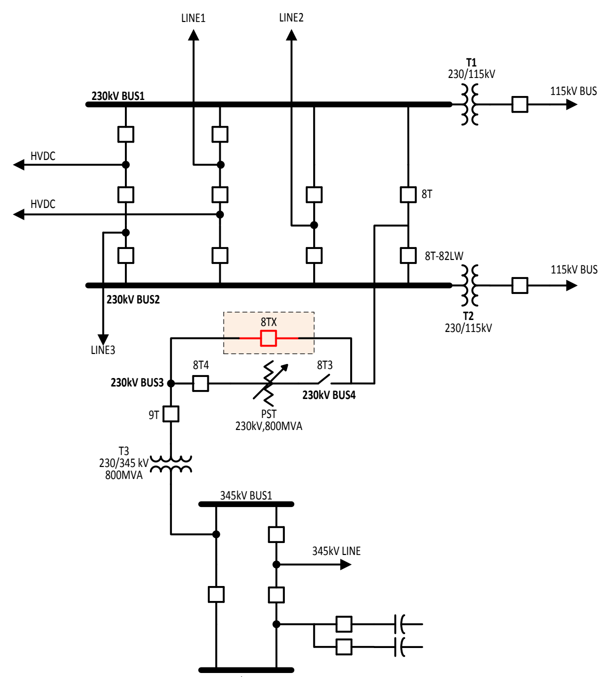


Fig. 1 230/345 kV Substation Single Line Diagram

An Electromagnetic Transients (EMT) study was carried out using PSCAD/EMTDC to determine the Ohmic value of the preferred pre-insertion resistor and the minimum insertion time required to ensure the new breaker would effectively eliminate the transformer inrush under any short circuit level condition so that the voltage depression would be limited to acceptable levels.

II. Simulation

A detailed three phase simulation model was set up in PSCAD/EMTDC.

A. Modeling

A three single-phase two winding transformer (230/230 kV) model was used as an equivalent representation of 230 kV phase shifting transformer. The saturation characteristic of PST was modeled and validated based on the measured V-I magnetization curve from the manufacturer as shown in Fig. 2.

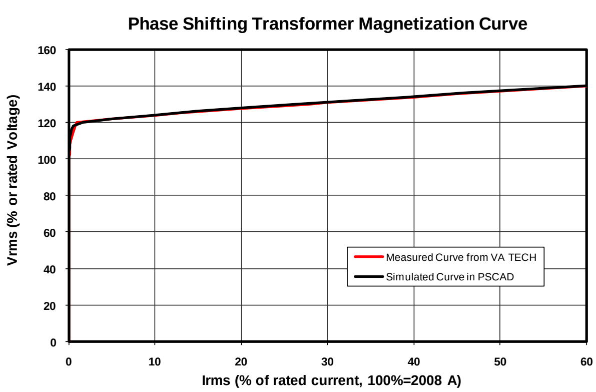


Fig. 2 Measured and modeled PST saturation characteristic

The parameters of the transformer leakage impedance and the saturation characteristic are given in Table 1

TABLE 1
PHASE SHIFTING TRANSFORMER PARAMETERS
MODELED IN PSCAD (AT 0 TAP)

Transformer MVA	800
Transformer kV	230
Leakage Impedance (p.u.)	0.113
Air core reactance (p.u.)	0.21
Knee voltage (p.u.)	1.195
Magnetizing Current (%)	0.10
Inrush Decay Time Constant (s)	5

The system was modeled in detail up to four buses away from the substation, and equivalent sources were used to represent the rest of the system. Transmission lines were represented using frequency dependent line models.

B. Methodology

Sensitivities studies were performed to optimize both the ohmic value and insertion time of the pre-insertion resistors taking into account variations in transformer saturation characteristics, remanent flux conditions, electrical system short circuit strength and the point on wave where energization occurs.

C. Results

1) Energization without Pre-insertion Resistors

If the Phase Shifting Transformer is energized without pre-insertion resistors and with all lines connected at the substation, the voltage can drop to as low as 0.6 pu if energizing all three phases simultaneously at the phase A voltage zero point and with 0.8 pu remanent flux on phase A as shown in Fig. 3. The adjacent system would be affected and subjected to large voltage drop in this case.

The most favorable case is energizing PST at phase A voltage peak and without remanent flux on any of phases. The highest voltage dip in this case is 0.1 pu. The voltages recovered to 0.95 pu in less than 0.15 s. The voltages did not drop to below 0.9 pu at any other stations in this case.

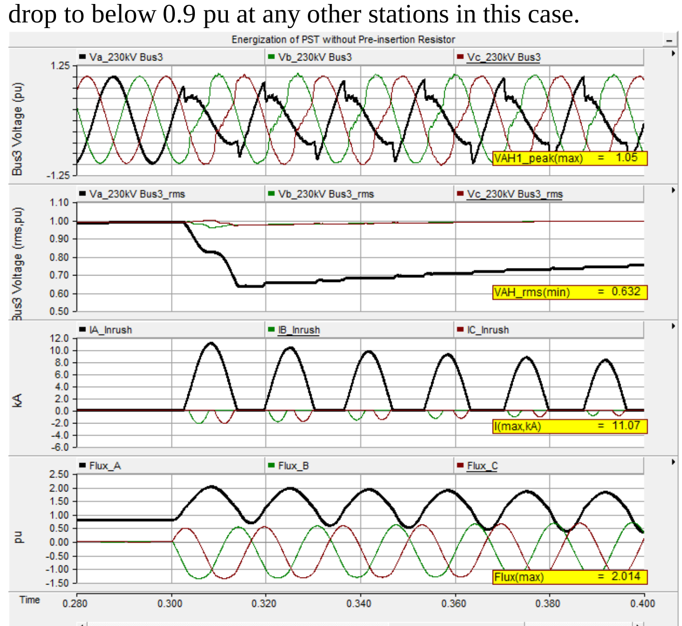


Fig. 3 Simulated waveforms for Energization of phase shifting transformer without pre-insertion resistors (Energized at Phase A voltage zero with 0.8 pu remanent flux)

If a weaker system is represented by taking out the 230 kV source providing the greatest contribution to the short circuit level, the system short circuit MVA would decrease to 2575 MVA and the voltage drops would be more severe.

2) Effect Ohmic Value of Pre-insertion Resistor

The effect of pre-insertion resistor ohmic value was investigated by varying the resistance from 0 to 500 ohms as shown in Fig. 4. All three phases of the breaker were closed simultaneously at Phase A voltage zero with 0.8 pu remanence on Phase A.

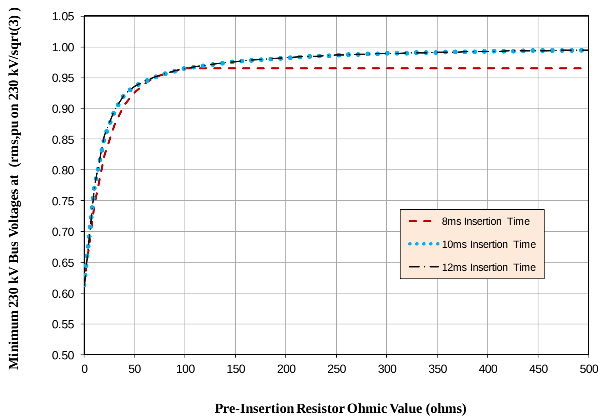
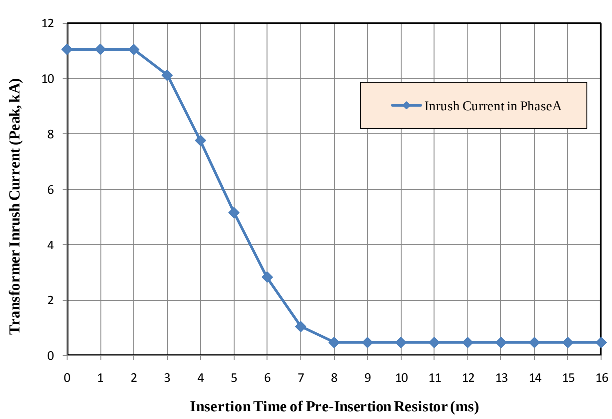


Fig. 4 Effect of ohmic value of pre-insertion resistor (Energize at Phase A Voltage Zero Crossing, 0.8 pu Remanence on Phase A)

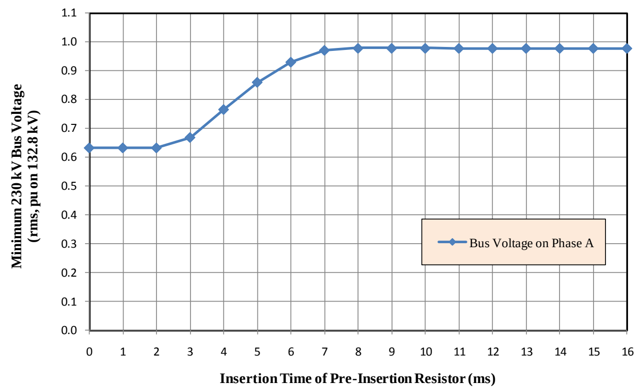
The voltage dip would be less than 10% if the pre-insertion resistor is greater than 40 Ohms. Larger values of pre-insertion resistance generally result in lower voltage dip but the improvement decreases rapidly above about 200 Ohms. Thus any standard value of closing resistor between 200 and 500 Ohms offered by a breaker supplier would provide similar performance in this application.

3) *Effect of Insertion Time*

Fig. 5 shows the simulated transformer inrush current and 230 kV bus voltage of Phase A as a function of resistor insertion time during energization at Phase A voltage zero crossing and 0.8 pu remanence on Phase A. The insertion time of the resistor has significant effect on the transformer inrush current and corresponding voltage drop.



(a) Transformer Inrush Current



(b) Minimum Voltage at 230 kV Bus

Fig. 5 Effect of insertion time of pre-insertion resistor (Energized at Phase A Voltage Zero Crossing, 0.8 pu Remanence on Phase A)

4) *Remanent flux condition and energization instant*

The remanent flux could be on any of three phases with different polarity and magnitude, and also the transformer can be energized at any instant between voltage peak and zero crossing on each phase.

Fig. 6 shows the calculated minimum line to neutral voltage among three phases at 230 kV bus with two combinations of remanent flux, 0.8 pu on one phase or ±0.8 pu on any two phases. The PST was energized at four instants with reference to Phase A voltage: voltage peak, voltage zero crossing, 50 degrees and 270 degrees after zero crossing.

Each set of curves includes variation of pre-insertion Ohmic value over the complete range from 400 Ohms to 1400 Ohms. It further confirms that the ohmic value does not affect the magnitude of inrush current provided it is greater than about 200 Ohms as already discussed in Section 2).

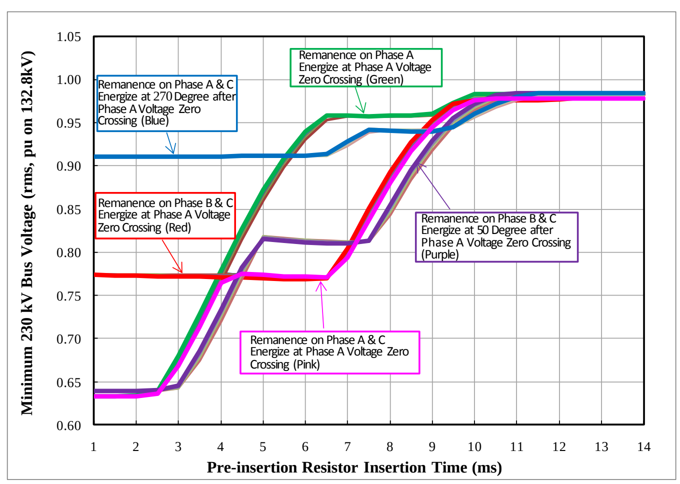


Fig. 6 Effects of Remanent Flux Conditions and Energization Instants

The results in Fig. 6 demonstrate that the effectiveness of the closing resistor depends on:

a) which phases have remanence, and

b) the instant of energization with respect to the phase(s) which have remanence

This dependence on closing instant can be completely eliminated only by ensuring that total minimum resistor insertion time is not less than 11 to 12 ms. (about 0.7 electrical cycle) Pre-insertion times less than about 8 ms (0.5 electrical cycle) provide limited benefit in energization events where the combination of remanence and energization instant are not favorable. The simulations were carried out on a 60 Hz system and thus the conclusions regarding insertion times would need to be adjusted for a 50 Hz system.

III. Comparison of Simulation to Actual Energization

Based on the study results, a breaker was ordered with specified values of 400 Ohm pre-insertion resistor which is a standard value offered by the breaker supplier and a minimum of 12 ms insertion time. Several energization events have taken place after the breaker was installed.

Unexpectedly high inrush currents were observed on the first energization. An investigation showed that this was due to insufficient resistor insertion time which appeared to be between 6 ms and 7 ms. In view of the poor performance, the supplier was requested to improve the insertion time to meet the specification.

Improved energization behavior was demonstrated in the subsequent energization events after the adjustment of insertion time. Sections A and B discuss the energization event before and after modification of breaker pre-insertion resistor insertion time.

A. High Inrush Energization Event Due to Insufficient Insertion Time (2008-10-15)

The phase shifting transformer was first energized with pre-insertion resistor on Oct 15, 2008. A high inrush current with peak value of 3.2 kA was observed in Phase A and this resulted in an unexpected large voltage drop of 17% as shown in Fig. 7.

The high inrush current was considered to be due to insufficient insertion time. The actual time that the resistor was inserted before main contacts were closed was measured to be about 6.8 ms, which was much less than the specified minimum insertion time of 12 ms.

Additional EMT simulations were performed to try and replicate the field measurements as shown in Fig. 8. In this simulation, the PST was energized at 130 degrees after phase A voltage zero crossing going positive with ±0.8 pu remanence on phases B and C. The simulation results demonstrated a relatively good agreement with the field results. The simulated inrush current was 3.9 kA and the corresponding voltage drop at the 230 kV bus was 10%. The small discrepancy is considered due to differences between simulated and actual remanent flux conditions.

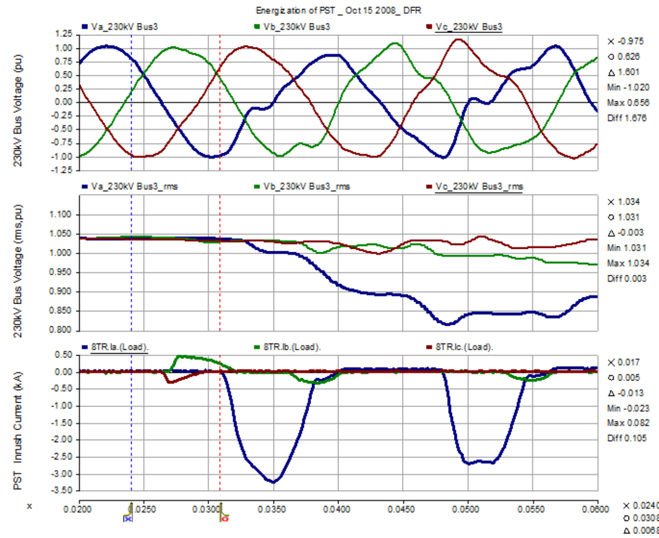


Fig. 7 Energization of phase shifting transformer with pre-insertion resistor insufficient insertion time of about 6.8 ms on Oct 15, 2008.

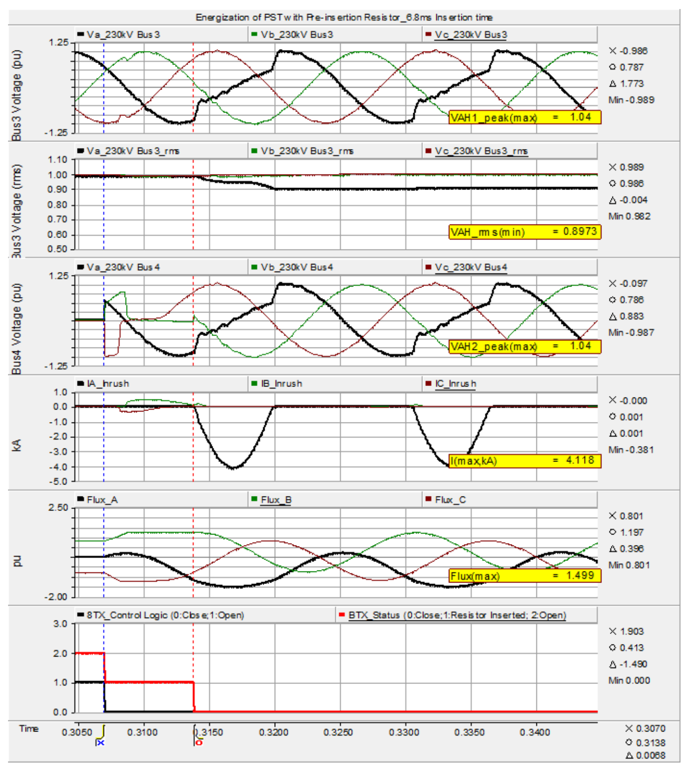


Fig. 8 PSCAD/EMDC Simulation Showing Energization of phase shifting transformer with 400 ohm pre-insertion resistor and 6.8 ms insertion time

B. Reduced Inrush with Increased Insertion Time

After the breaker was modified to increase effective insertion time, the phase shifting transformer as well as auto transformer were energized again to document the improvement in performance.

The recorded DFR traces of the energization on July 7, 2010 are shown in Fig. 9 for the PST and Fig. 10 for the autotransformer.

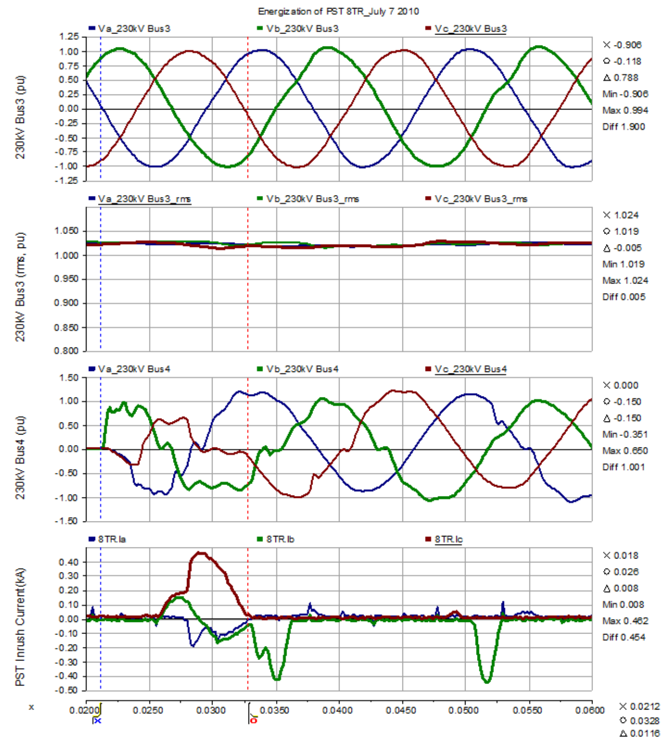


Fig. 9 Field Energization of phase shifting transformer (PST) after pre-insertion resistor insertion time was adjusted (July 7 2010)

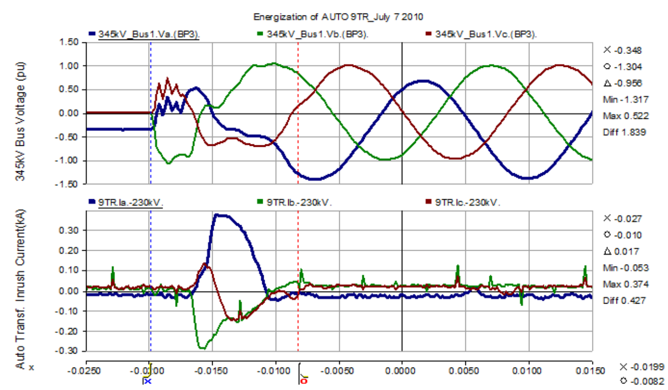


Fig. 10 Field Energization of 230/345 kV auto-transformer after pre-insertion resistor insertion time was adjusted (July 7 2010).

Measurements of the energization waveforms indicate that an effective insertion time of about 11.6 ms was achieved in both the PST and auto transformer energization cases. The inrush currents were limited to less than 0.5 kA which is very close to the maximum expected value based on the simulations as shown in Fig. 11.

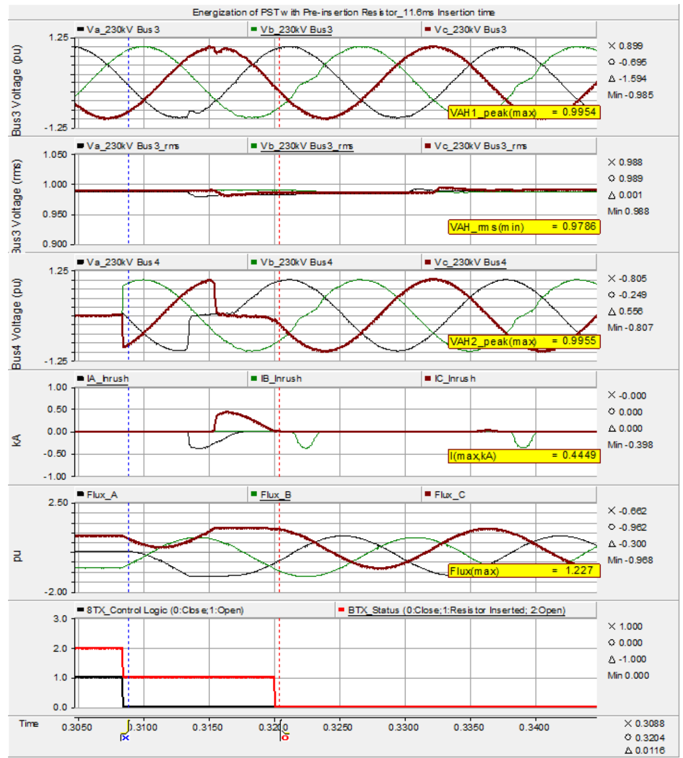


Fig. 11 PSCAD/EMDC Simulation of Energizing phase shifting transformer with 400 ohm pre-insertion resistor and 11 ms insertion time

IV. Conclusions

The simulations and field energization oscillograms of a 230 kV phase shifting transformer and a 230/345 kV auto-transformer indicate that both the Ohmic value and insertion time are important to ensure satisfactory performance of pre-insertion resistors for limiting inrush currents during transformer energization.

In critical applications where it is important to limit the voltage dip due to inrush currents, it is crucial to specify the minimum insertion time should not be less than about 0.7 electrical cycles. This insertion time is longer than typically needed for transmission line energization and therefore breakers which are capable of providing adequate insertion times may not be readily available.

The actually achieved insertion time of the circuit breaker must be verified by field testing and adjusted if necessary to ensure that it meets the specification.

V. References

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VI. ACKNOWLEDGMENT

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VII. BIOGRAPHIES

Jingxuan Hu received her Bachelor's degree in Electrical Engineering in 1995 (China) and her Masters degree in Computer and Electrical engineering in 2001 (Canada). She has over fifteen years experience in high voltage technologies and power equipment, protection and digital relays, power system stability and electromagnetic transient (EMTP) studies; Subsynchronous resonance phenomena analysis and small signal stability studies; HVDC system control and modeling; Series and shunt compensations; Equipment design studies such as breaker TRV, line and transformer energization, live line maintenance.
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