# Analysis of Damaging Open-Phase Event on a Healthy Shunt Compensated 500 kV Line Initiated by Unintended Trip

T. Martinich, M. Nagpal, S. Manuel

*Abstract*-- **Shunt reactors are applied on medium or long extra high voltage transmission lines to compensate for the natural capacitive charging currents which otherwise would cause over-voltages under light load conditions or when the line is temporarily operated open at one end and energized from a weak source. However, as the degree of shunt compensation approaches or exceeds 65%, these reactors can, during contingencies, become the cause of hazardous over-voltages during unbalanced one or two open-phase conditions on the healthy line. This paper reports on an incident that occurred on the BC Hydro system when a long 500 kV line having 72% shunt compensation was unintentionally tripped under load, eventually leading to a two open-phase condition for an extended period of time when one of the line terminal breakers failed while attempting to interrupt a current having a slowly decaying dc component. The ensuing temporary over-voltage was high enough and persisted long enough to produce failure of one line-end surge arrester.**

**This paper provides the actual recordings of the voltages and currents at both terminals of the 500 kV line. This is followed by analysis, starting with consideration of simple L-C circuits which demonstrate the presence of a resonance near power frequency during the two open-phase condition. A step-by-step approach is taken towards duplicating the field recordings of the temporary over-voltages using an EMT type program starting with a linear network model followed by progressively including the nonlinear effects of reactor saturation, surge arrester conduction and, finally, the effects of corona losses on the overhead line. Mitigation alternatives to prevent the occurrence of similar incidents are briefly discussed.**

***Keywords*: Shunt Compensated Lines, Open-phase, Transmission Line Over-voltages, Series Resonance.**

## I. Introduction

SHUNT reactors are commonly applied on medium or long extra high voltage (EHV) lines to control the over-voltages that can occur at the receiving end by counteracting some of the capacitive effects of the line. This practice is referred to as reactive shunt compensation. Shunt compensation is an effective method of controlling or limiting the line over-voltages to within the safe limits under light load or after sudden load rejection. Circuit breakers on EHV lines have independent poles. Consequently, these lines can experience uneven phase operations, such as by design during single-pole trip and reclose (SPTR) operation or by failure of a breaker pole to open or to close. During the unbalanced open-phase conditions, one or two phases of the line remain connected to the source and the remaining phase(s) disconnected. During such unbalanced conditions when there is no fault on the line, the shunt reactor(s) on the isolated phase(s) and the line's inter-phase and phase-to-ground capacitances form a series resonant circuit. When the degree of shunt compensation is high, the tuning frequency of the circuit can approach power frequency. As a result, application of shunt compensation intended to control over-voltages on the line can actually lead to hazardous over-voltages across the shunt reactors, surge arresters, breakers and instrument transformers connected to the isolated phase(s). The intent of this paper is to share the knowledge gained from the analysis of a damaging open-phase event with other utilities either having or planning on highly compensated lines. Model details are provided which will allow the reader to conduct simulations with other numerical computation tools.

This paper reports on an incident that was triggered by unintended tripping of a long 500 kV line under load in the BC Hydro system. This initiated a sequence of events which led to the failure of one breaker pole to interrupt, so that one phase was left energized from one end for many cycles. Under this condition, excessive temporary resonant over-voltages were induced in the two open phases which ultimately resulted in the failure of one of the line-end surge arresters. Re-striking transients caused by the failed breaker pole caused the failure of the surge arrester at the other end. Before presenting a discussion on the induced over-voltages that occurred during the unbalanced open-phase condition, a brief general description of the BC Hydro EHV system, including characteristics of the line and connected equipment involved in the incident, will be provided. Waveforms of the disturbance retrieved from high speed digital fault recorders will be presented. The over-voltages observed are examined by considering a screening technique based on steady state

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simplified linear network analysis identifying a series resonance condition. The results are validated by detailed transient simulations. Results of these studies are presented, demonstrating the effects of including nonlinear effects of magnetic saturation of the shunt reactor cores, surge arrester conduction, and the corona losses on the line. Finally, mitigation alternatives are presented to avoid future occurrences of damaging over-voltage under similar conditions.

## II. B.C. Hydro System

BC Hydro, the third largest utility in Canada, possesses major hydro-electric generation assets, primarily located in the northern (Peace River) region of the province and in the south eastern (Columbia River) region. This generation is remote from the Vancouver area in the south-west corner of the province where most of the demand for electricity is concentrated. The “backbone” transmission system consists of long 500 kV lines that carry bulk Peace and Columbia power to the major load center. Transmission paths are sectionalized but some lines are as long as 330 km. The majority of the 500 kV lines have midline series compensation to achieve dynamic and transient stability. In addition, 500 kV lines longer than 120 km have shunt compensation at one or both line terminals to achieve 30% or 60% or higher compensation of the positive sequence line capacitance. For security, due to the radial nature of the network, key transmission sections are equipped with both high speed single-pole and three-phase reclose schemes.

### *A. Details of 500 kV Line in the Peace System*

Figure 1 shows a simplified one-line diagram of circuit 5L2 and its connected equipment which was involved in the incident. This line is one of three parallel 500 kV transmission paths between G. M. Shrum (GMS) Generating Station and Williston (WSN) switching station. The line is 277 km long and is fully transposed. The 50% series compensation at midline was bypassed immediately after the initial trip-out of the line. Positive sequence capacitive line charging is about 375 MVAr at 525 kV. This line is 72% shunt compensated using a set of 135 MVAr reactors at each end of the line. The original Peace transmission system, with the initial stage of it completed in the mid 1960’s, was not designed and equipped for single-pole trip and reclose. Power system technology of the day was not considered reliable enough for selective phase tripping of long lines, hence the shunt reactors were not equipped with neutral reactors. The single-phase shunt reactors (5RX2) at GMS are fixed and the ones at WSN (5RX4) are switchable. The saturation characteristics of these reactors as well as the detailed parameters for 5L2 are provided in the Appendix. There is a set of 396 $kV_r$ surge arresters 5SA26 protecting GMS 5RX2 and a set of 372 $kV_r$ arresters 5SA34 protecting WSN 5RX4, as indicated in the diagram. The arresters at GMS have a higher voltage rating because, as a major generating station, GMS is operated at a somewhat higher voltage than WSN.

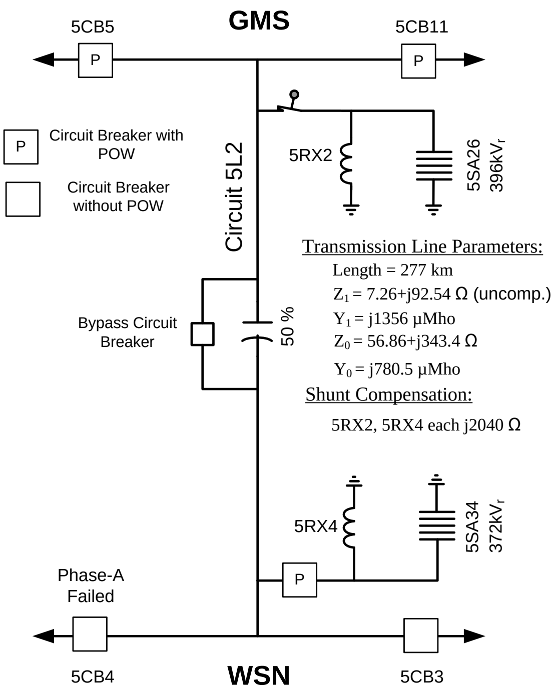


Fig. 1. Simplified 5L2 one-line diagram – Peace Region

### *B. Point-on-Wave Control*

The original 500 kV Peace River system used air-blast circuit breakers equipped with closing resistors to limit the transmission line switching surges to 2.0 pu However, by the mid 1990’s, a more compact 500 kV line design was adopted, requiring that line switching surges be limited to 1.7 pu At the same time, a decision was made to phase out the old generation of breakers having closing resistors in order to avoid the complexity and ongoing high maintenance costs associated with closing resistors. BC Hydro deployed a new generation of circuit breakers into the 500 kV system and implemented Point-On-Wave (POW) control schemes on the lead-end breakers for automatic reclose or for manual and supervisory line pick-up [1]-[2]. Instead of closing all three breaker poles simultaneously, a POW scheme is capable of closing each pole independently at the optimum point on the voltage waveform so as to control switching surges. This scheme, together with appropriately rated surge arresters at the line terminals and also at midline of longer lines, provide improved insulation performance and reduce the voltage stress on the connected equipment.

To maintain system stability, single-shot high speed automatic reclose is attempted after line trips. Though the reclose scheme for 5L2 is designed to initiate single-pole trips for single phase-to-ground faults and three-pole trip for all multi-phase faults, in practice, the scheme is set to operate only in three-phase mode for all faults. The GMS bus is the lead (or master) end for auto-reclose and the associated breakers 5CB5 and 5CB11 are equipped with POW closing. 5CB5 is the first breaker to close. After successful closing of the first breaker, 5CB11 closes all three poles simultaneously. At WSN (follow end for high speed auto-reclose), 5CB3 and 5CB4 are not equipped for POW closing and will reclose simultaneously, with some delay, after the GMS end closes.

## III. The Incident and Waveform Analysis

On 16 April, 2012, during work at GMS to replace a free-standing CT on 5L2, an unintended protection operation resulted in the primary protection tripping the line while under load. During a sequence of events which lasted 6.85 seconds from initiation of the inadvertent trip to complete line isolation and lockout, one breaker (WSN 5CB4 Phase A) and two surge arresters (WSN 5SA34 Phase B and GMS 5SA26 Phase A) failed.

Voltage and current waveforms recorded by the digital fault recorders at the GMS and WSN stations were synchronized and are plotted in a single chart in Figure 2. The upper three traces correspond to the instantaneous phase-to-ground voltages followed by the three line currents at the GMS end of 5L2. The lower six traces correspond to the voltages and currents at the WSN line terminal. For improved resolution, the waveform traces are limited to a period of 680 ms. Phase B and Phase C voltage waveforms at WSN, during the two open-phase condition, exhibit noticeable "peak clipping". This is not due to surge arrester conduction or other nonlinear effects; it is because the over-voltages were so high that they exceeded the pre-set range of the digital fault recorder. The recordings at GMS using a different scaling do not have this problem.

During the 100 ms prior to the reference time, T = 0, the line is isolated and in a ring-down mode as a result of the initial line trip. Time T = 0 represents the initiation, by the POW controller at GMS, of the auto-reclose of Phases B and C of 5CB5 (but not yet Phase A) while the WSN end was open. When the POW closed Phase A at GMS about six cycles after Phases B and C, it did so at a non-optimal point on the voltage wave, initiating a large slowly decaying DC component in the current through 5CB5 Pole A during the line re-energization. However, for some reason, line protection at GMS (lead end) initiated a re-trip of 5L2 almost immediately after Phase A reclosed but pole A of 5CB5 continued to conduct because there was no zero crossing until the WSN terminal (follow end) reclosed three-phase. The line reclosing at WSN created a Phase A current zero at GMS and the slowly decaying DC component in the current was then transferred to the WSN Phase A breakers.

The line re-trips by protection mis-operation upon Phase A reclose at GMS initiated an immediate trip of the WSN end of 5L2. With the DC component in the Phase A line current persisting while the breaker pole A was attempting to open at WSN, interruption was not possible until a zero crossing occurred, some 13 cycles later. Subsequently, there were multiple restrikes inside 5CB4 Pole A, as evidenced by the spikes in the WSN Phase A line current on the lower right hand side of Figure 2, indicating that 5CB4 had failed.

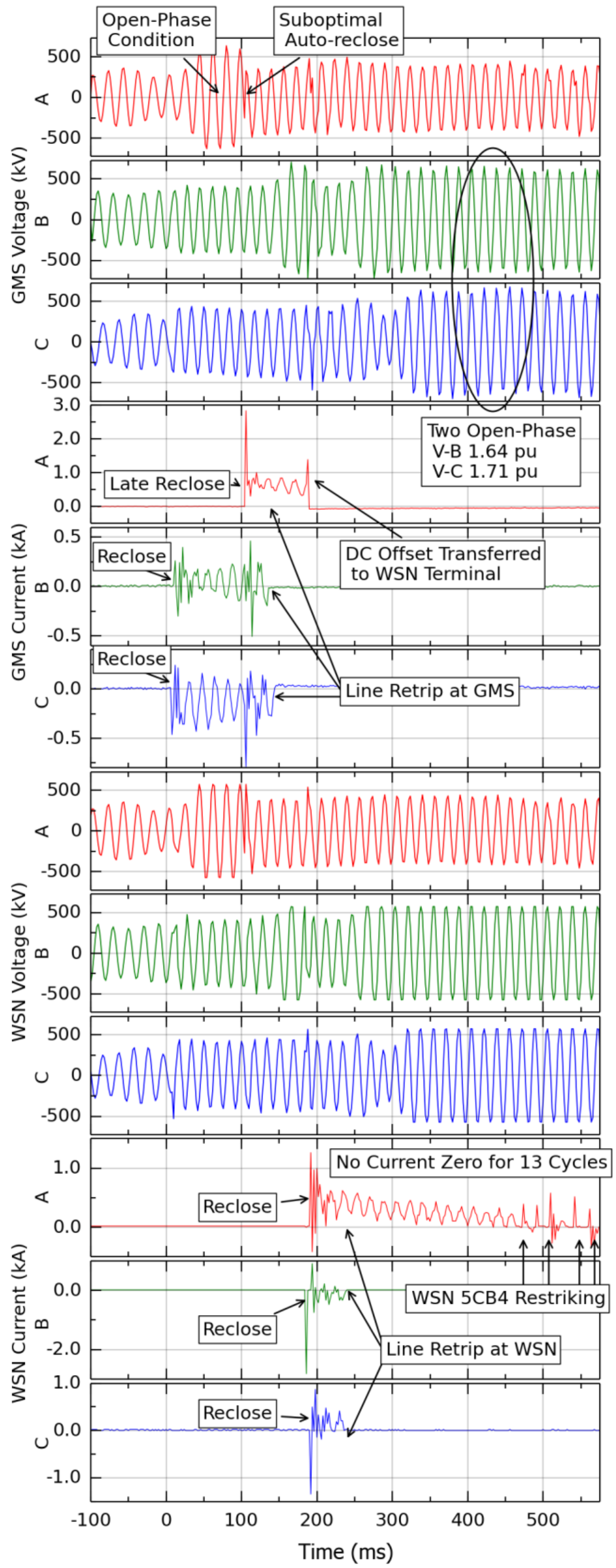


Fig. 2. Traces from high-speed digital fault recorders at GMS and WSN.

The failed WSN breaker pole kept Phase A energized for many cycles (5L2 already open three-phase at GMS), resulting in high over-voltages on the open B and C phases. The maximum instantaneous Phase B to ground voltage was about 1.64 pu and Phase C voltage was about 1.71 pu, as measured at GMS. The failure of the Phase B surge arrester at WSN and the Phase A arrester at GMS occurred sometime beyond the time frame of Figure 2. The prolonged period of re-striking generated many high switching transients which eventually damaged Phase A of 5SA26 at GMS. Additional waveforms, analysis and a detailed description of the sequence of events can be found in [3].

## IV. Modeling and Simulations – Two Open Phases

### A. *Results of Simplified Steady State Analysis*

References [4]-[5] discuss the induced over-voltages that can occur on shunt-compensated EHV transmission lines during resonant or near resonant open-phase conditions, planned or unintended. The subject is introduced by considering a less rigorous and less labor–intensive analysis approach which neglects nonlinear effects and assumes balanced line construction and steady-state conditions. Lumped parameter equivalent L-C circuits converted into the familiar series resonant topology are presented and formulae provided which calculate the theoretical magnitudes of the induced open-phase over-voltages. The steady-state analysis also provides the resonant frequencies and the compensation that would produce resonance at power frequency for the open-phase conditions. By way of a caution, both references emphasize that the simplified network analysis approach should be viewed as a screening technique to identify important cases to be studied more rigorously with EMT simulations using more detailed models. In reality, actual power systems are not perfectly balanced, line parameters are distributed and over-voltages will be limited by nonlinear effects. Reference [4] demonstrates that including the limiting effects of transmission line corona losses and shunt reactor saturation effects produces more realistic simulations of induced over-voltages, which the authors confirmed by field measurements. Reference [5] investigates the effects of line construction details on the resonance and induced open-phase over-voltages. Theoretical magnitudes of the over-voltages on the open phase(s) can be calculated using the line capacitance data and the inductance of the phase reactors. Additional information on unbalanced open-phase operation of shunt-compensated transmission lines and the expected over-voltages can be found in Chapter 4 of [6].

Applying the simplified steady state analysis method of [4]-[5] and the parameters provided in the Appendix, the resonant frequencies of 5L2 for the one and two open-phase conditions were calculated. Results are listed in Table 2. The Table also provides the degree of compensation that would be required to shift the resonance so as to coincide with the power frequency. For the two open-phase condition, the resonant frequency is extremely close to 60 Hz. The actual compensation on 5L2 is practically identical to that required to cause the natural frequency to coincide with the power frequency. Therefore, high over-voltages can be expected, and there would be a concern of damage to the line-connected equipment on the open phases. However, for the one open-phase condition on 5L2, the resonant frequency is 55 Hz and the degree of shunt compensation required for resonance at power frequency is 0.8586 pu. Therefore the theoretical open-phase voltage is expected to be much lower than for the two open-phase case.

TABLE I
5L2 Open-phase conditions – resonant frequencies and theoretical compensation required for resonance at power frequency

| Contingency | Resonant Frequency | Compensation for Resonance @ 60 Hz |
|---|---|---|
| Two open phases | 60.2 Hz | 0.712 pu |
| One open phase | 55.0 Hz | 0.8586 pu |

### B. *EMT Simulation with no Nonlinear Effects Modeled*

Electromagnetic transients simulations with a detailed 5L2 transmission system model validated the findings of the steady-state analysis confirming near power frequency series resonant over-voltages for the two open-phase condition. The EMT model of 5L2 accounted for line length, the geometric arrangement and diameters of the conductors (four-conductor bundle per phase) and the transpositions of the phases, and the shunt reactors (represented as linear inductors) at the line ends. This enables the effects of unbalances (unequal inter-phase capacitance), the distributed nature of the parameters of the line separating the two sets of reactors, and the line resistive losses to be accounted for, all of which are not considered by the steady-state lumped parameter approach. The simulation shown in Figure 3 corresponds to 5L2 (initially with three phases open at the GMS end) becoming energized from one phase only when Phases B and C open but Phase A remains energized from the WSN 500 kV bus. For the purpose of illustrating the basic series resonance, the nonlinear effects of corona losses on the line, reactor saturation and surge arrester conduction were not included. A temporary over-voltage of several per unit develops on Phases B and C, indicating a resonant condition.

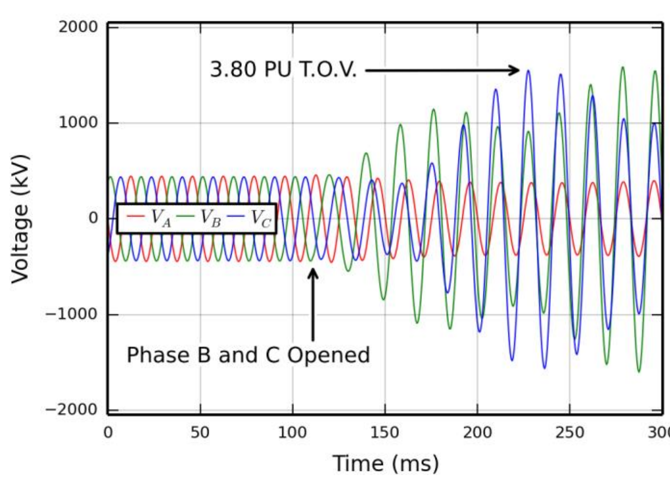


Fig. 3. Electromagnetic transient simulation of the two open-phase condition for a 277 km long 500 kV line with 72% shunt compensation. No nonlinear effects were modeled.

The electromagnetic transients model was extended to include nonlinear effects in an effort to simulate the measured temporary over-voltages during the two open-phase condition. It is instructive to see the significance of each of the nonlinear effects on the resulting TOVs by adding these successively, starting with saturation of the reactor cores, then the 372 kV surge arresters 5SA34 at WSN, and finally, including a model for corona losses on the line.

### C. *With Reactor Saturation Effects Included*

The banks of single-phase shunt reactors, 5RX2 at GMS and 5RX4 at WSN, have the same ratings and magnetizing characteristics. The voltage versus magnetizing current has a linear slope of 2040 Ω up to the kneepoint voltage of 475 $kV_{rms}$ (1.65 pu) phase to ground and a slope of 668 Ω above the kneepoint. Each reactor bank was modeled as three single-phase two-slope nonlinear inductors having a solidly grounded neutral. Figure 4 shows the same switching scenario for the two open-phase simulation as was assumed for Figure 3, but magnetic saturation effects are now included. As can be seen, saturation has reduced the temporary over-voltages on the open B and C phases from 3.8 pu observed for the linear model to a maximum below 2.3 pu.

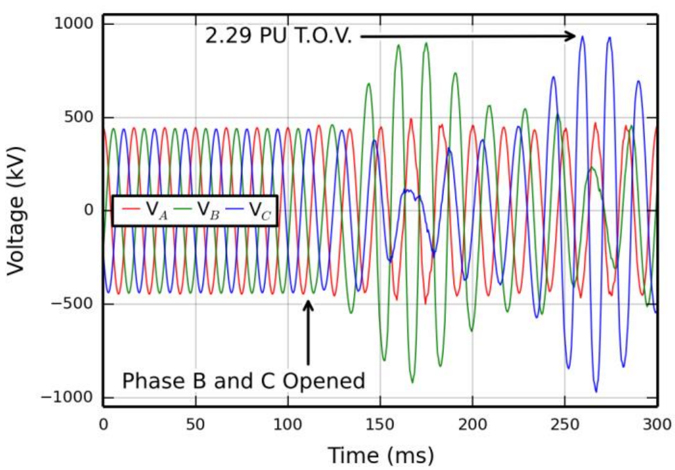


Fig. 4. Electromagnetic transient simulation of the two open-phase condition for 5L2. Saturation characteristics of the shunt reactors were modeled.

### D. *Surge Arrester Conduction Added*

The surge arresters 5SA26 at the GMS end of 5L2 have a voltage rating of 396 kV, which is significantly higher that the 372 kV arresters 5SA34 at WSN. For simulation of the unbalanced 5L2 two open-phase condition, only the effects of the WSN arresters need to be considered (no failures occurred for 5SA26 Phase B or Phase C). The arrester manufacturer provides Tables of performance and protective data according to trade name, class and voltage rating which enables modeling for EMT simulations. The 5SA34 metal oxide arresters are 372 $kV_{rated}$ IEC Class 4 with an energy capability of 10.8 $kJ/kV_{rated}$, an MCOV of 301 $kV_{rms}$ phase-to-ground, and a 1 second TOV capability of 431 $kV_{rms}$. For purposes of constructing the EMT model for the ZnO arrester, two additional pieces of information are required: (1) the plot of AC peak voltage across the arrester versus peak current and (2) the residual voltage for a $10kA_p$ 8/20µs current wave. The arrester manufacturer usually provides the voltage-current characteristic as a semi-logarithmic plot where current can range from less than 1 mA to 10,000 A or more. The voltage, on a linear scale, is given in per unit based on the residual voltage. For 5SA34, the maximum residual voltage is 847 $kV_{peak}$. Table II provides the voltage-current characteristic that was used for the ZnO model of these arresters.

TABLE II
ARRESTER 5SA34 VOLTAGE-CURRENT CHARACTERISTIC BASED ON MANUFACTURER'S DATA FOR A 372 $kV_{RATED}$ 10.8 $kJ/kV_R$ METAL OXIDE ARRESTER.

| Arrester Current | Arrester Voltage | |
|---|---|---|
| $A_{peak}$ | $V_{pu}$ on 10kA 8/20µs | $V_{peak}$ |
| 1.0 | 0.698 | 609354. |
| 10.0 | 0.720 | 628560. |
| 50.0 | 0.746 | 651258. |
| 100.0 | 0.760 | 663480. |
| 500.0 | 0.814 | 710622. |

The simulation of the resonant temporary over-voltages when 5L2 is switched into the two open-phase condition is shown in Figure 5. Reactor saturation and arrester conduction have been accounted for. As can be seen by comparison to Figure 4, the addition of the arrester models has greatly reduced the TOVs. The TOV on Phase B is about 1.77 pu and on Phase C it is about 1.74 pu. These values are only slightly higher than the measured over-voltages.

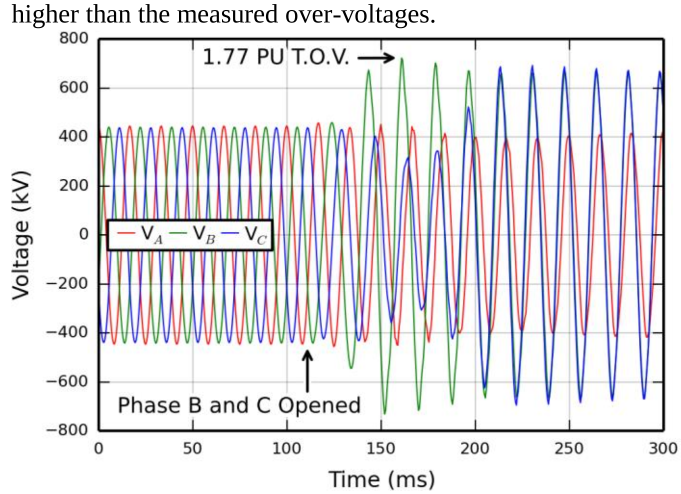


Fig. 5. Electromagnetic transient simulation of the two open-phase condition for 5L2. Saturation characteristics of the shunt reactors and arrester conduction were modeled.

### E. *With 5L2 Corona Effects Added*

In view of the effectiveness of the surge arrester models at WSN to reduce the TOVs to levels close to the actual measurements, corona losses on 5L2 could not have played a significant role during the two open-phase event of 2012. However, it seems reasonable to assume that, for TOVs that were measured as being above 1.6 pu, some corona would have been present on Phases B and C and the losses would have provided some damping of the over-voltages.

Reference [4] describes a method exploiting Peek's work, where corona losses are modeled as nonlinear resistors connected phase-to-ground at the mid-point of the line. Corona conduction is neglected for voltages less than the critical inception voltage and above this level the slope of the V-I characteristic is the corona resistance, calculated according to [4]. The critical corona onset voltage on 5L2 for the atmospheric conditions that existed at the time of the 2012 event is not known accurately. However, assuming a corona onset voltage of 1.65 pu and using an experimentally-determined corona resistance of 60 Ohms, the resulting corona model was added to the EMT system model containing the saturable reactor and ZnO arrester models. Switching 5L2 into the two open-phase condition was then simulated. Figure 6 shows the resulting phase-to-ground voltages at the GMS end of 5L2, where all nonlinear effects have been accounted for. The TOVs have been reduced slightly and are very close to the measured 1.64 pu to 1.71 pu. Figure 7 compares the simulated to the measured phase-to-ground voltages at GMS and, as can be seen, the comparison is excellent. The relative mean squared error, which is the mean of the error squared normalized by the mean of the field recording squared, is 2.8%, 9.7% and 14.1% for the A, B, and C phases, respectively.

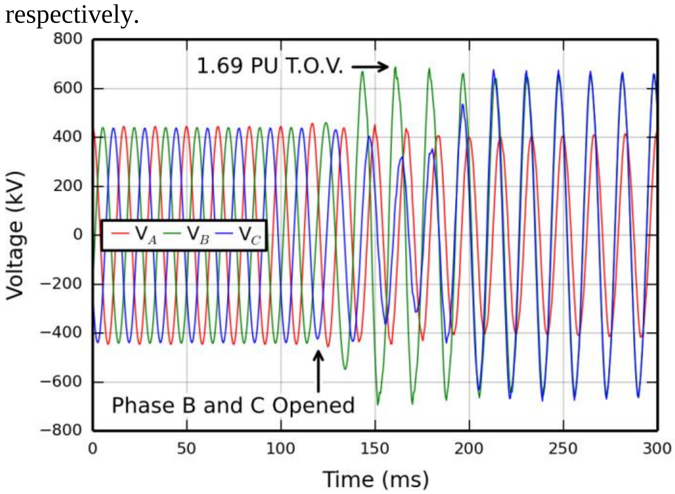


Fig. 6. Electromagnetic transient simulation of the two open-phase condition for 5L2. Saturation characteristics of the shunt reactors, arrester conduction, and corona effects on the overhead line were modeled.

## V. Mitigation Alternatives

This section briefly discusses mitigation alternatives considered to prevent reoccurrence of similar temporary resonant over-voltage incidents within the BC Hydro 500 kV system. These alternatives are:

1. Addition of neutral reactors
2. Trip the switchable reactors
3. Improve the POW scheme, and,
4. Devise Protections solutions

The addition of neutral reactors would detune the series resonance but this alternative is not possible because the phase reactor neutral point is not properly insulated for this duty. If the old reactor banks have to be replaced in the future, the new ones can be designed to accommodate neutral reactors. The tripping of the switchable reactor (at WSN) would have to be done by operator action after every line trip and successful auto-reclose. This would not be convenient in lightning storm season when 500 kV lines can experience several lightning strikes followed by their trip and reclose on a given day. The new generation of POW controllers use sophisticated algorithms, exploiting Prony analysis [7] to achieve a more successful closing on voltage zero across the breaker pole. BC Hydro will be deploying a second generation of POW in future applications. Finally, there does not appear to be a reliable protection system to safeguard the line against prolonged over-voltages caused by unbalanced open-phase no-fault conditions.

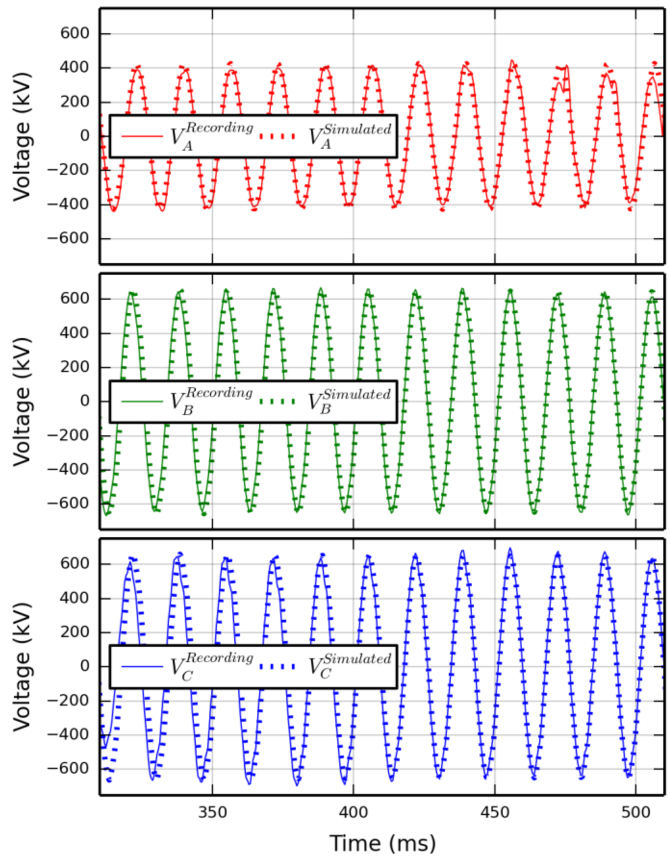


Fig. 7. The comparison of the simulated to the measure phase-to-ground voltages at GMS for 310 ms to 510 ms. Saturation characteristics of the shunt reactors, arrester conduction, and corona effects on the overhead line were modeled.

## VI. Conclusions

This paper has demonstrated, through analysis of simplified equivalent L-C circuits, digital simulations, as well as by analysis of an actual destructive mis-operation, that a high degree of shunt compensation, but with no neutral reactor, designed to control over-voltages on a long EHV transmission line, can unintentionally result in hazardous temporary over-voltages. For the actual event reported here, the critical case occurred when there was breaker failure and unbalanced open-phase conditions of the unfaulted line. The phase reactors can become part of a series resonant circuit, together with the phase-to-ground and inter-phase line capacitances, where the tuning frequency approaches power frequency. The excitation of the resonance, provided by capacitive coupling to the energized phase(s), can result in high temporary over-voltages. Modeling the effects of saturation of the shunt reactor cores and, in particular, the conduction in the 372 kV surge arresters at WSN must be accounted for in the modeling for unbalanced open-phase simulations. The representation of corona losses on the line was found to be of secondary importance in this particular case. With the nonlinear effects modeled, EMT simulations could duplicate, to a good degree of accuracy, the temporary over-voltages measured for the two open-phase condition.

Surge arresters, though they successfully protected the 5L2 line terminal equipment during the incident described in this paper, failed themselves due to exposure to temporary over-voltage and to restrike transients and this resulted in the temporary unavailability of the line.

A reliable protection scheme is not available to safeguard the line from exposure to the prolonged over-voltage hazard under no-fault open-phase conditions. The addition of neutral reactors to de-tune the resonance and enable SPTR operation cannot be applied to the existing grounded phase reactors and must await the replacement of the old reactor banks at some time in the future. The second generation of point-on-wave controllers will be used to minimize pole scatter during closing.

## VII. Appendix

Figure 8 shows a typical guyed V tower for this flat-configuration circuit. The average height of the conductor above ground at the tower and the average conductor sag are 26.7 m and 10 m, respectively. Each phase comprises a bundle of four 316.1 mm$^2$ ACSR conductors in a 45.7 cm by 45.7 cm square arrangement.

<u>500 kV Reactors: WNS 5RX4 and GMS 5RX2:</u>

Each Set is Comprised of 3 Single-phase Units
Neutral point is solidly grounded
Reactors are individually protected by ZnO Arresters.
Slope of the Exciting Voltage versus Current Characteristic:
j2040. Ohms to Kneepoint of 475 kV$_{rms}$ phase-to-ground
j668. Ohms above 475 kV$_{rms}$

<u>5L2 Parameters:</u>

Line Length: 277 km
Conductor Type: 316.1 mm$^2$ ACSR
Phase Bundle:
4 Conductors/phase
45.72 cm x 45.72 cm square
Conductor Outer Diameter: 2.4130 cm
Diameter of Conductor Steel Core: 0.67564 cm
Conductor DC Resistance: 0.09050 Ohm/km
Z1 = 7.26 + j92.54 Ohms
Y1 = j1356 µMho
Z0 = 56.86 + j343.4 Ohms
Y0 = j780.5 µMho
Line Insulation Level: About 2.0 pu
Corona Inception Voltage: Assumed value 1.65 pu (673.6 kV$_{peak}$ Phase-to-Ground)
Transpositions: 92.2 km and 183.1 km from GMS
Phasing at GMS end of the Line: C-B-A
Phasing at WSN end of the Line: A-C-B

<u>WSN 500 kV Bus (with 5L2 out-of-service)</u>

Z1 = 1.857 + j18.60 Ohms
Z0 = 5.304 + j46.55 Ohms

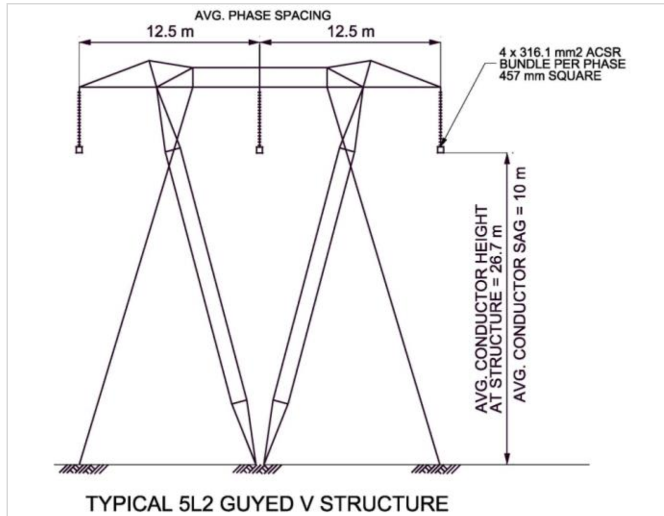


Fig. 8. 5L2 construction details.

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