PQSoft Case Study

Lightning Transient Overvoltage Evaluation

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Abstract:

This case study presents a wind plant substation lightning transient overvoltage evaluation. A high-frequency transient model was created to simulate the lightning transients and resulting overvoltages and arrester energy duties. A high-frequency model was required to accurately represent the lightning phenomena. MOV surge arresters were evaluated as the power conditioning alternative.

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RELATED STANDARDS

IEEE Std. 1313.2

GLOSSARY AND ACRONYMS

CF	Crest Factor
DPF	Displacement Power Factor
PF	Power Factor
PWM	Pulse Width Modulation
THD	Total Harmonic Distortion
TPF	True Power Factor

INTRODUCTION

A wind plant substation lightning transient overvoltage evaluation case study was completed for the system shown in Figure 1. The case study investigated the potential for severe high-frequency transient overvoltages on substation transformer primary and secondary buses during lightning strikes on the terminating transmission line and wind collector circuit bus. The power conditioning mitigation alternative of MOV surge arresters was also evaluated.

The simulations for the case study were completed using the PSCAD® program. A high-frequency transient model was created to simulate the lightning transients and resulting overvoltages and arrester energy duties. A high-frequency model was required to accurately represent the very high lightning transient frequencies. The lightning surge was assumed to be a current source (e.g., 10 kA) with a very fast rise time (e.g., 8x20 μsec).

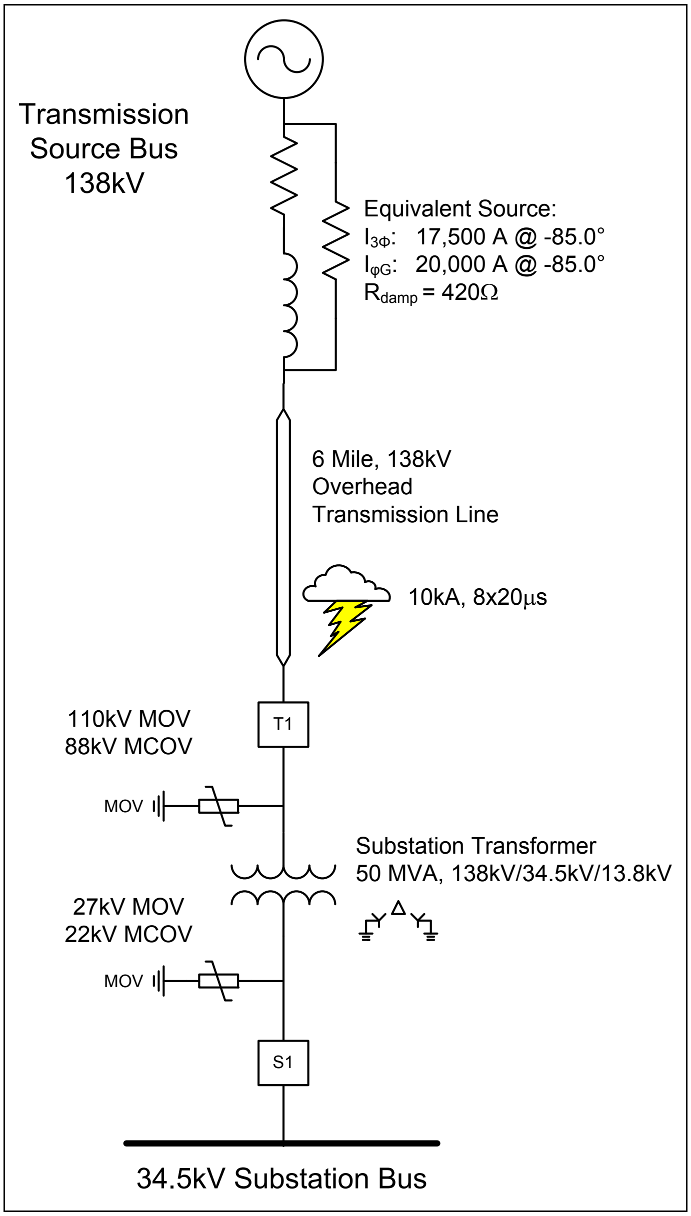

Figure 1 - Illustration of Oneline Diagram for Lightning Transient Analysis

SIMULATION RESULTS

For wind plants, the principal risk to equipment insulation is impulsive transients caused by lightning. Lightning transients may enter a substation by various means, including coupling through the substation power transformer from exposed high-voltage transmission lines and direct or indirect strikes to open air equipment.

For the lightning simulations, it was assumed that the wind farm substation is shielded against direct strokes and that a 10kA surge enters the substation due to a lightning flash terminating on the overhead shield wire or structure with a subsequent flashover (a.k.a., back flashover) to a phase conductor or by a lightning flash terminating on the phase conductor due to a shielding failure.

Back flashover is a flashover of insulation resulting from a lightning stroke to part of a network or electrical installation that is normally at ground potential. When back flashover occurs, a portion of the surge current will be transferred to the phase conductors through the arc across the insulator strings. Often, the back flashover causes a temporary phase-to-ground fault that must be cleared by circuit breakers.

The high-frequency transient simulation model included a 138kV wind plant substation and a 6-mile transmission line supplying a 50 MVA, 138/34.5/13.8kV substation transformer. The representation of the system short-circuit equivalent at the 138kV source substation included:

Three-phase ($I_{3\varphi}$) fault current: .... 17,500 A @ -85.0° (4183 MVA)
Single-line-to-ground ($I_{\varphi G}$) fault current: .... 20,000 A @ -85.0° (4780 MVA)

These values were converted to ohms for the PSCAD representation, which included a three-phase voltage source with positive and zero sequence impedances and a 420Ω damping resistor.

The 6.0 mile, 138kV transmission line was modeled using the following data:

Length: .... 6.0 mi
Phase Conductor: ....795 kcmil (Tern) 45/7 ACSR (OD = 1.063”, R_{DC}=0.114Ω/mi)
Ground Conductor:.. 3/8" EHS (OD = 0.385”, R_{DC}=5.550Ω/mi)
Tower Configuration:..TAN-1
Ground Resistivity:..100 Ω•m

The traveling wave frequency dependent phase model in PSCAD was used to represent the transmission line. The frequency dependent phase model is basically a distributed RLC traveling wave model, which incorporates the frequency dependence of all parameters. This model represents the frequency dependence of internal transformation matrices.

The program calculates the line constants for the transmission line before each simulation begins. The 60 Hz impedance values from the line constants output were compared with the transmission line impedances to assure that the line was modeled correctly. The calculated surge impedance of the transmission line was approximately 420Ω. A portion of the line constants output includes:

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Per-Unit Quantities Based On:    Base Voltage:  138.00 kV, L-L, RMS
                                     Base MVA:  100.00 MVA

NOTE: Base values are set using Output File Data
      Display Options component in Editor View.

SEQUENCE RESISTANCE Rsq [p.u.]:
       + Seq. Self: 0.376270541E-02
       0 Seq. Self: 0.194032234E-01

SEQUENCE REACTANCE Xsq [p.u.]:
       + Seq. Self: 0.230921994E-01
       0 Seq. Self: 0.835736057E-01

SEQUENCE SUSCEPTANCE Bsq [p.u.]:
       + Seq. Self: 0.702081297E-02
       0 Seq. Self: 0.397031721E-02
```

A 110kV (88kV_{MCOV}) station class MOV surge arrester was modeled at the transmission line termination point. The ratings for the arrester included:

Rated Voltage (Duty Cycle):	110 kV	
Maximum Continuous Operating Voltage (MCOV):	88 kV	
Maximum Energy Discharge Capability:	9.8 $kJ/kV_{rated\ MCOV}$	
Maximum Energy Discharge Capability:	862.4 kJ	
10 kA, 8x20 µsec Discharge Voltage:	274 kV	(2.43 per-unit)

A 27kV (22kV_{MCOV}) station class MOV surge arrester was modeled on the secondary winding of the substation transformer. The ratings for the arrester included:

Rated Voltage (Duty Cycle):	27 kV	
Maximum Continuous Operating Voltage (MCOV):	22 kV	
Maximum Energy Discharge Capability:	9.8 $kJ/kV_{rated\ MCOV}$	
Maximum Energy Discharge Capability:	215.6 kJ	
10 kA, 8x20 µsec Discharge Voltage:	64.8 kV	(2.30 per-unit)

A traditional inductive transformer model generally looks like an open circuit to the very high frequency lightning transient. The 60 Hz transformer model can be improved by adding capacitances between windings and from the windings to ground. This type of model will act as a capacitive voltage divider to transfer a portion of the surge from the primary to the secondary windings. The bushing and winding capacitance values included in the model were C_{hg} = 8ηF, C_{lg} = 8ηF, and C_{hl} = 12ηF.

Other substation equipment, such as circuit breakers and instrument transformers, were represented by their stray capacitances to ground. Typical stray capacitance values of substation equipment are provided in Annex B of IEEE Std. C37.011. The values used in the simulation model included:

Effective Capacitance (High-Side of Transformer)	15,000 ρF
Effective Capacitance (Low-Side of Transformer)	3,000 ρF

The high-frequency transient simulation model was based on the substation oneline diagram and other information, such as the 138kV transmission line specifications. The steady-state voltage at the 138kV substation bus was 1.05 per-unit prior to the transient event. For the worst-case analysis, it was assumed that all of the 34.5kV collector circuit breakers would be open during the simulations. Two lightning surges were simulated; one on the terminals of the 138 kV transmission line entering the substation and the other on the 34.5kV bus on the transformer secondary.

Case 1 involved a lightning strike to one of the terminals of the 138kV transmission line entering the substation. The specification of the current waveform was a 10kA magnitude, with an 8x20μsec characteristic (Phase A). The lightning surge current waveform is shown in Figure 2.

Figure 3 shows the simulated transformer primary voltage for Case 1. The peak transient voltage was 272.323kV (2.42 per-unit). Figure 4 shows the corresponding transformer secondary voltage. The peak transient voltage was 56.437kV.

The peak current for 88kV$_{MCOV}$ arrester on the transmission line terminal (transformer primary) was 9.3 kA and the maximum arrester energy was 51.8kJ, which is approximately 6.0% of the assumed arrester energy capability of 862.4kJ. The simulated protective margin for the 550kV BIL rating for the transformer primary winding was determined using:

$$\left(\frac{\text{Insulation Level}}{\text{Arrester Discharge Voltage}} - 1\right) * 100 = \%\text{Margin}$$

$$\%\text{Margin} = \left(\frac{550\text{kV}}{272.323\text{kV}} - 1\right) * 100 = 101.97\%$$

The protective ratio for the transformer primary winding was 2.02 (550kV BIL / 272.323kV). An adequate margin has a ratio greater than 1.20 (see IEEE Std. 1313.2).

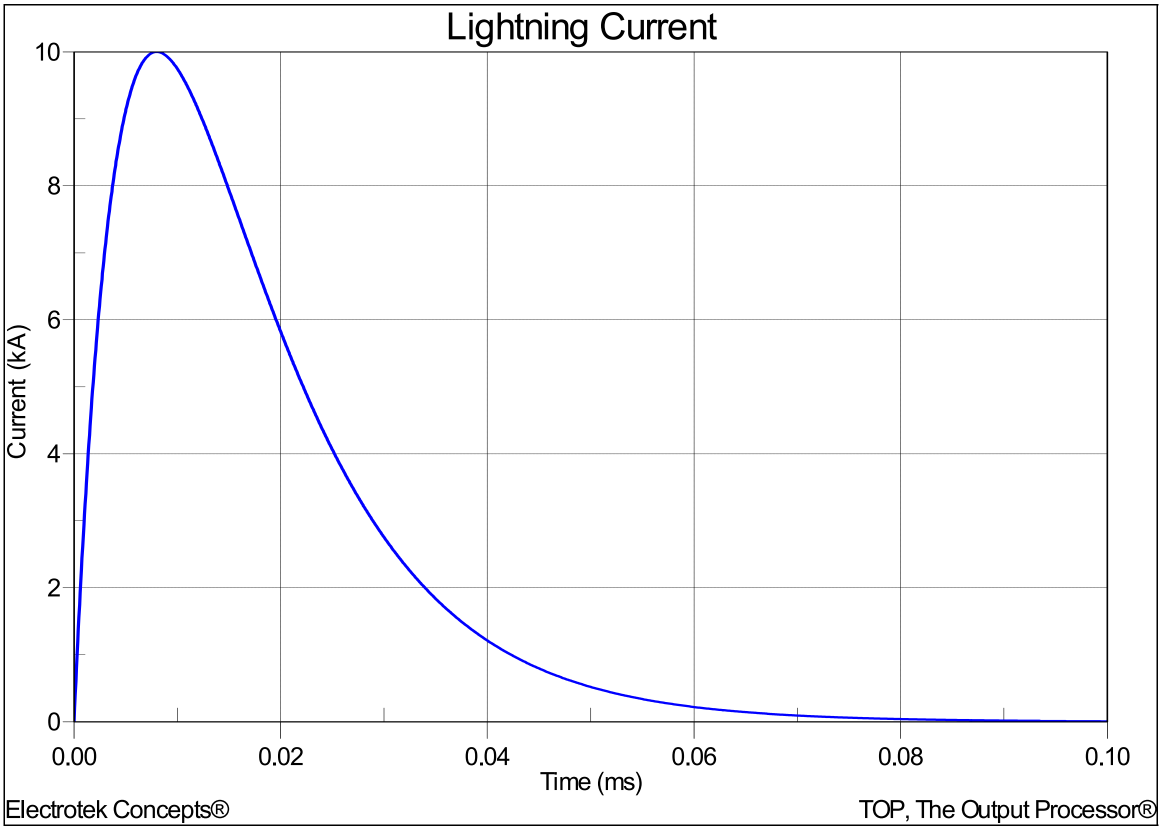

Figure 2 - Illustration of the Simulated Lighting Surge Current Waveform

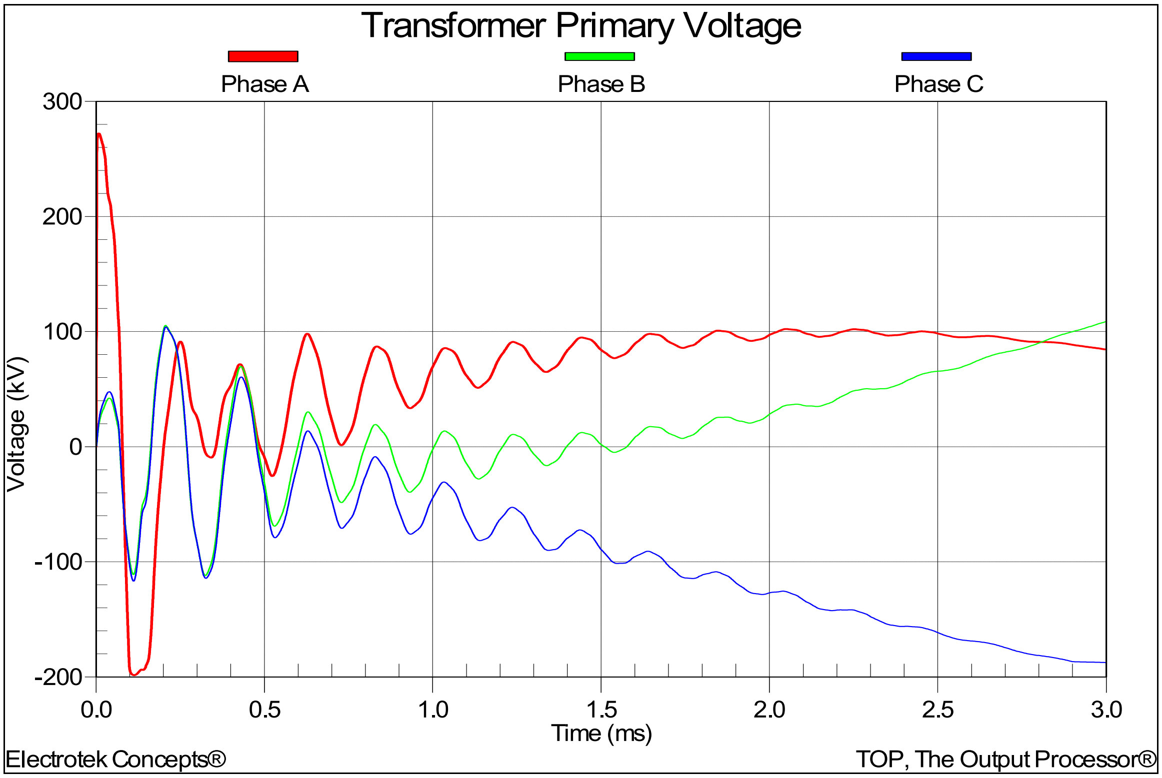

Figure 3 - Simulated Transformer Primary Voltage for Case 1

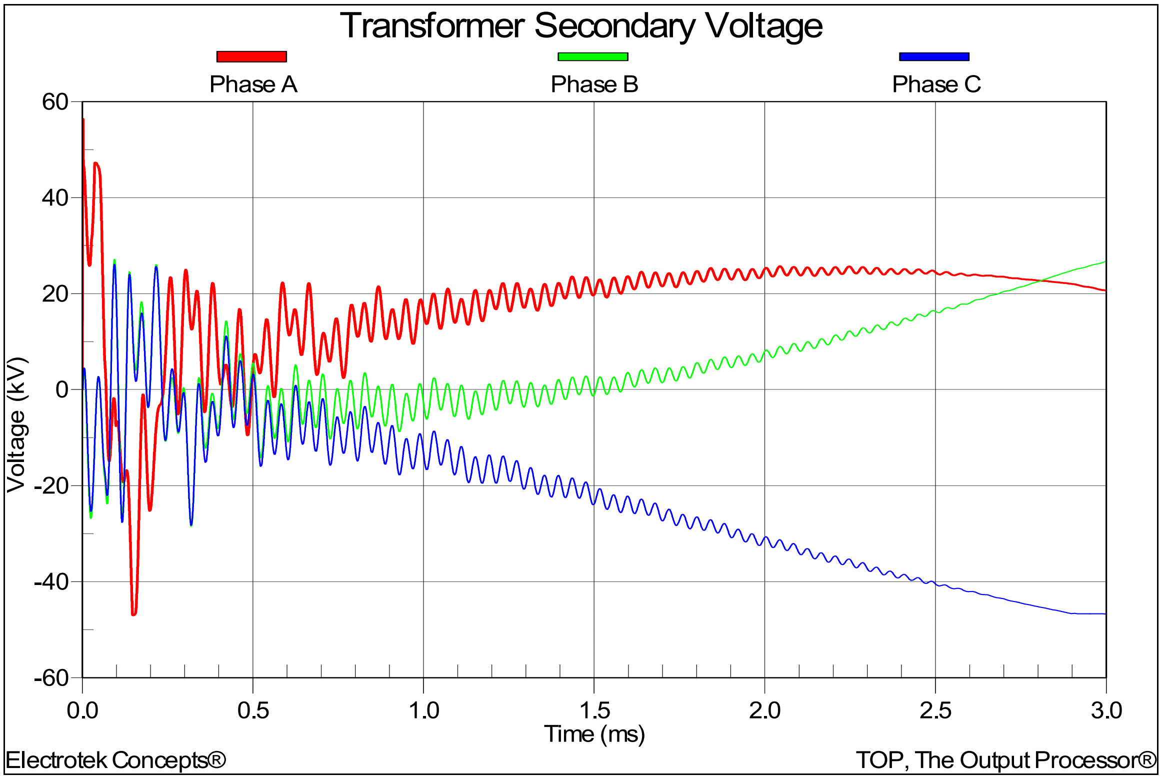

Figure 4 - Simulated Transformer Secondary Voltage for Case 1

Case 2 involved a lightning strike to the 34.5kV bus (transformer secondary winding). The specification of the lighting surge current waveform (see Figure 2) was a 10kA magnitude, with an 8x20μsec characteristic.

Figure 5 shows the simulated transformer secondary voltage for Case 2. The peak transient voltage was 64.719kV (2.29 per-unit). Figure 6 shows the corresponding transformer primary voltage. The peak transient voltage was 31.042kV.

The peak current for 22kV$_{MCOV}$ arrester was 9.9kA and the maximum arrester energy was 13.6kJ, which was approximately 6.3% of the assumed arrester energy capability of 215.6 kJ.

The simulated protective margin for the assumed 200kV BIL rating of the transformer secondary winding was determined using:

$$\left(\frac{\text{Insulation Level}}{\text{Arrester Discharge Voltage}} - 1\right) * 100 = \%\text{Margin}$$

$$\%\text{Margin} = \left(\frac{200\text{kV}}{64.719\text{kV}} - 1\right) * 100 = 209.0\%$$

The protective ratio for the transformer primary winding was 3.09 (200kV BIL / 64.719kV). An adequate margin has a ratio greater than 1.20 (see IEEE Std. 1313.2).

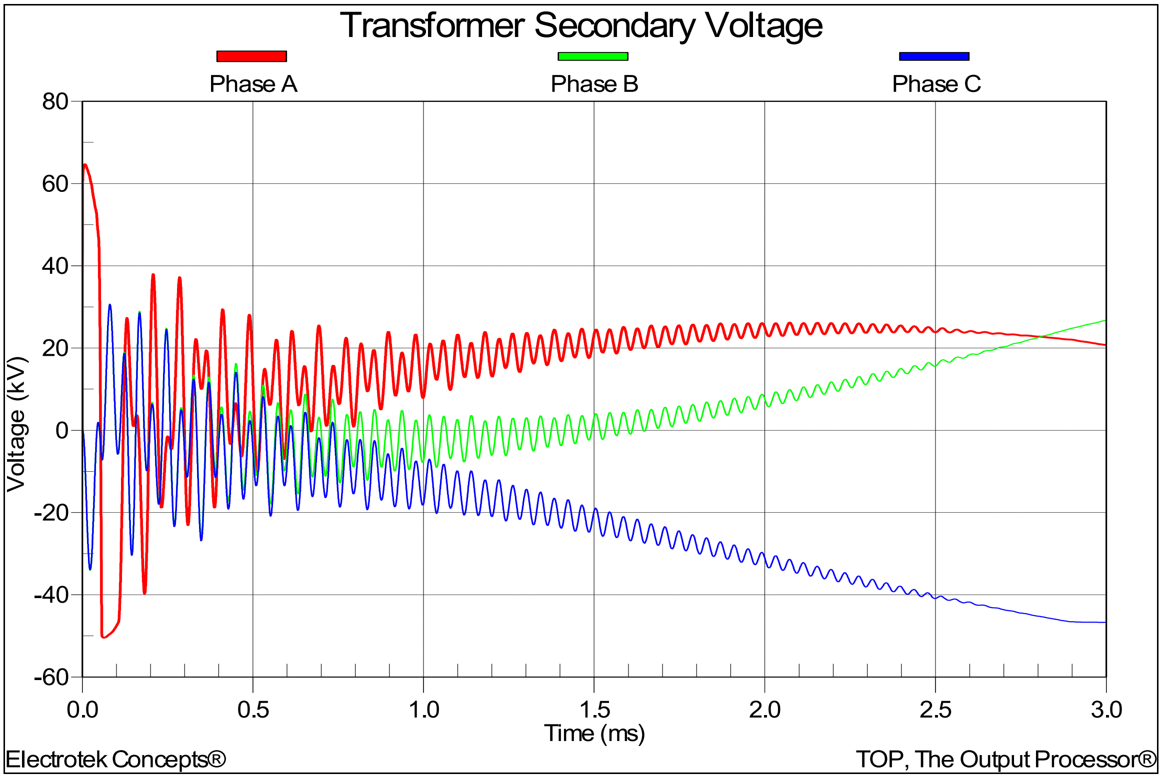

Figure 5 - Simulated Transformer Secondary Voltage for Case 2

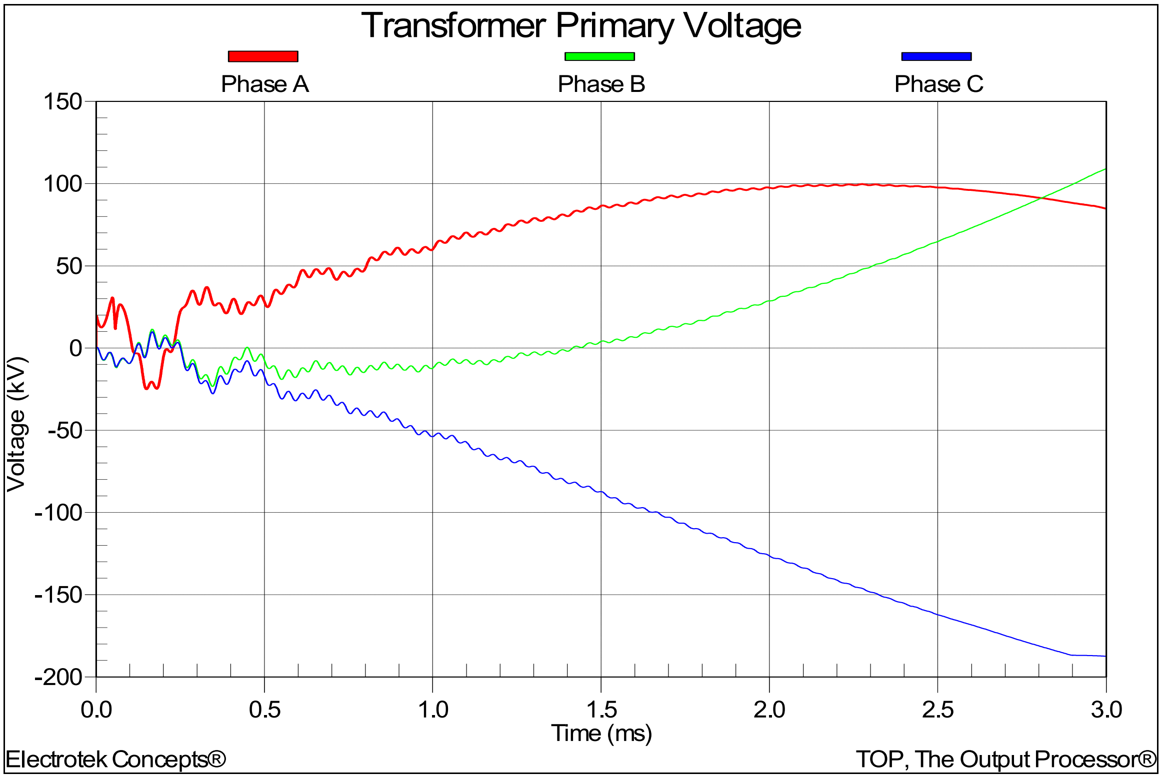

Figure 6 - Simulated Transformer Primary Voltage for Case 2

SUMMARY

This case study summarized a wind plant substation lightning transient overvoltage evaluation. A high-frequency transient model was created to simulate the lightning transients and resulting overvoltages and arrester energy duties. A high-frequency model was required to accurately represent the lightning phenomena. MOV surge arresters were evaluated as the power conditioning alternative.

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