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AEP's 765kV Transmission Line Model Validation for Short Circuit and System Studies

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SUMMARY

NERC standards MOD-032 and MOD-033 require applicable entities to periodically review and validate power system models, including transmission line model parameters of interest to protective relaying engineers. AEP has already developed a tool to validate transmission line PI-models from relay fault records. However, for 765kV untransposed lines where self-mutual coupling has a significant impact on the apparent impedance seen by a relay during a fault, the PI-model is no longer sufficient and a detailed EMTP/EMTDC transmission line model should be used instead to calculate the apparent impedance. Furthermore, due to the effect of the self-mutual coupling, the apparent phase-to-phase impedances measured by a relay for different types of faults at the same location are different. Unfortunately, there are an insufficient number of fault records which could be used to support line model validations. To close the loop of untransposed 765kV line modeling and apparent impedance validation, a PSCAD model for AEP untransposed 765kV transmission system has been developed and validated through limited fault records. Based on the PSCAD model, the apparent impedances for various faults are calculated and benchmarked with those calculated by a line constant tool.

KEYWORDS

Mutual impedance, model validation, transmission line, fault record, 765kV, NERC compliance, PSCAD, EMTP/EMTDC

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Introduction

NERC reliability compliance standards MOD-032 and MOD-033 were approved for use in 2014 [1]. These standards collectively require transmission owners (TOs) and transmission planners (TPs) to validate the power system models used in system planning and short-circuit simulations and provide evidence of validation [2][3]. One of the requirements per the standards is the validation of sequence impedance parameters of transmission lines. Since the early 2000s, AEP has developed a system, called the Substation Data Repository (SDR), to automatically retrieve Common format for Transient Data Exchange (COMTRADE) fault record files from relays, and upload them to a central server for easy access by stakeholders [4]. Recently AEP engineers developed software to utilize the event files on the SDR system to validate the line sequence impedances in AEP's short-circuit models.

However, the self-mutual coupling of untransposed 765kV lines will affect the apparent impedances calculated by a relay for different types of faults. This means that 6 independent apparent impedances (Za, Zb, Zc, Zab, Zbc, Zac) must be validated dependent upon the corresponding fault type and sequence pi-model network, which are typically used in short-circuit simulations, are no longer sufficient in this case. For instance, phase A to phase B apparent impedance Zab should be validated through a phase A to phase B to ground (AB-G) fault record; while Zbc should be validated through a phase B to phase C to ground (BC-G) fault record. For a simple 6-element distance relay, there must be 6 types (A-G, B-G, C-G, AB-G, BC-G, AC-G) of fault records, respectively, as the evidence of validation for all apparent impedances as needed. Unfortunately, only a limited number of relay fault records are available for validation of line impedances. To assist with this, a EMTP/EMTDC type distributed transmission line model should be used instead to simulate the fault and calculate the lump apparent impedances as an alternative to fault records. AEP has developed and utilized the PSCAD/EMTDC 765kV transmission system model to conduct fault simulations and used the simulated results as indirect but still trustworthy evidence of validation for all the 6 line apparent impedances.

In this paper, the AEP 765kV transmission system line models are developed within PSCAD. An apparent impedance calculation algorithm also is summarized and results will be presented to demonstrate how fault types would impact the apparent impedance calculation. The algorithm used to validate line models using fault records and the software AEP engineers have developed will be used to validate the PSCAD model. Lastly, faults on the AEP 765kV system will be simulated and then the line apparent impedances calculated by the PSCAD will be compared with those calculated by the line constant calculation tool.

PSCAD 765kV System Model Development and Apparent Impedance Calculation Algorithm

A. PSCAD 765kV Transmission Line Models

AEP 765kV transmission lines are modeled within PSCAD as overhead lines using the predefined PSCAD transmission line model library, which contains a variety of pre-constructed transmission line towers. The tower components are used to define the conductor and ground wire geometric configurations. Line length and other special transmission line configurations, such as ground wire open loop, phase transpositions, and line reactors, are also modelled in detail as line sections. Figure 1 illustrates the modeling by taking one of the AEP 765 kV lines modelled in PSCAD as an example.

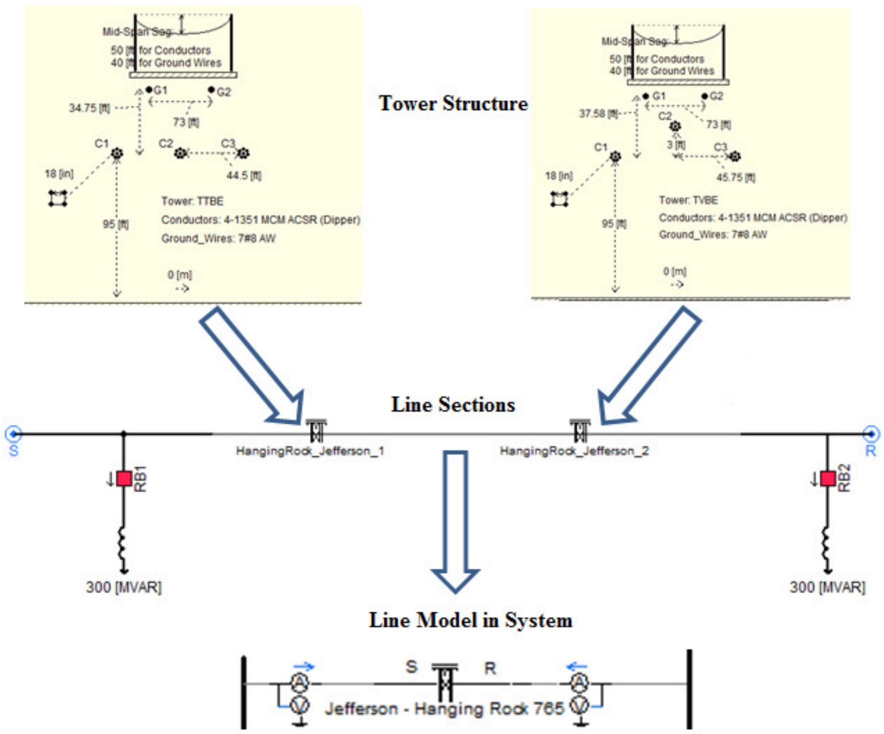

Figure 1 AEP PSCAD Overhead Transmission Line Model

B. PSCAD Apparent Impedance Validation

PSCAD provides Line Constants Program (LCP) to calculate all frequency domain parameters (or constants) required of a transmission line so that distributed transmission systems can be convolved into a two-port, time domain representation and interfaced with the EMTDC network. However, the results from the LCP cannot directly be used for comparison with the sequence network pi-model which is used in commercial short circuit (SC) calculation software. To be compatible with using fault records from relays to validate the line model and with SC model, a lump pi-model parameter estimation algorithm should be applied to both the PSCAD model fault simulation results and the field fault records. Thus, an apparent line-apparent impedance validation (LIV) algorithm is developed in the PSCAD environment to calculate the pi-model of a given transmission line in fault simulation.

There are many models that can be used to represent transmission lines. A common model used for medium length transmission lines and commercial short-circuit study tools, such as PSS/E and ASPEN Oneliner, is the PI model [5]. This model divides the transmission line charging currents into two shunt capacitances and places them at either end of the transmission line. The line model representation is shown in Figure 2.

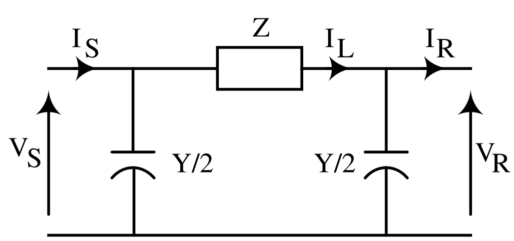

Figure 2 TransmissionLine PI Model Estimation

If we have the current and voltage phasors at two ends of the transmission line PI-model, we can derive the line impedance and shunt capacitance as in (1) and (2), respectively.

$$Y = 2\left(\frac{V_S + V_R}{I_S - I_R}\right) \quad (1)$$

$$Z = \frac{V_S^{\ 2} - V_R^{\ 2}}{I_R V_S + I_S V_R} \quad (2)$$

where V_S is the sending end voltage, Vr is the receiving end voltage, I_S is the sending end current, and Ir is the receiving end current; and they are all phasors.

Further, in order to determine positive, negative, and zero sequence impedances of the line, the sending and receiving end voltages and currents are replaced with their respective sequence voltage and current values such that (2) yields to:

$$Z_{0,1,2} = \frac{V_{S\,0,1,2}^{\ 2} - V_{R\,0,1,2}^{\ 2}}{I_{R\,0,1,2} V_{S\,0,1,2} + I_{S\,0,1,2} V_{R\,0,1,2}} \quad (3)$$

PSCAD provides an online Fast Fourier Transform (FFT) and can determine the harmonic magnitude and phase of the input signal as a function of time, and computations are performed on-line, at each sampling instance, and are based on a sampled data window of the preceding input signal cycle. The output of the FFT, which are the sequence voltage and current phasors, are fed into equation (3) to calculate the sequence network pi-model impedances. By applying a single line to ground fault at the external bus end of the line whose model is to be estimated, the LIV gives the estimated impedance of each sequence.

Algorithm and Software for Line Impedance Validator Using Fault Records

AEP engineers have developed the Line Impedance Validator (LIV) to process the fault records and estimate the sequence network PI-model of a transmission line [6]. Synchronized fault records at both ends of the transmission line are mandatory in this model validation for obtaining synchronized voltage and current phasors for a fault at two ends of a transmission line. After valid raw data is gathered and assigned to LIV, the software then performs a full-cycle Discrete Fourier Transform (DFT) and data resampling on the data to acquire the current and voltage sequence synchronized phasors. Then line apparent sequence network impedance and shunt capacitance are calculated using equation (1) and (2) for each time sample within the fault period. Multiple valid fault records are used to generate statistical information so that the PI model is validated through multiple valid event data and at the same time to identify and eliminate bad data. In the AEP SDR system, a large amount of valid fault records are available because a single fault could trigger valid fault records in pairs of relays for multiple lines as external faults. A screening process is integrated in the LIV to find all the qualified records for a particular line model validation. Take one of the AEP 765kV transmission line in Indiana as an example: fault records are recorded in SDR from 2010 to 2015, and five valid fault records are found by this automatic screening process to be the evidence of model validation. And LIV calculates the statistics of the sequence network pi-model impedances as shown in Figure 3.

In Figure 3, the black circle represents the 10% error margin area where the center is the impedance used in AEP's current short-circuit calculation model. The colored (red and blue) dots are the LIV estimated impedance of all the five records. The averaged impedance comparison with the current SC calculation impedance, and the impedance estimated from corresponding PSCAD line model using the method introduced in previous section, are listed in Table I. As we can see from the table, the results show that the calculated positive and zero sequence impedance are both within acceptable tolerances. The validation process ensures that the PSCAD model is sufficiently accurate and could be used to calculate the line apparent phase-to-phase impedances and perform other system studies.

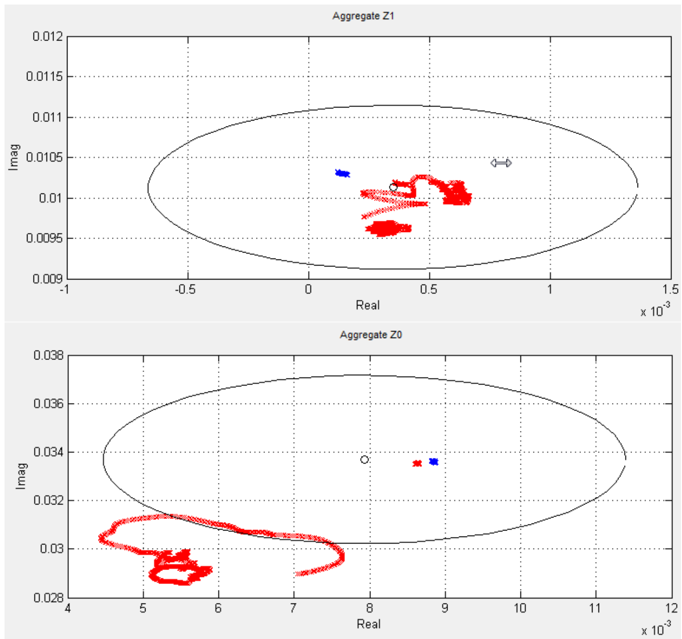

Figure 3 Estimated +/0 Sequence Impedance in per unit from Fault Records

Table I. P.U. Impedance Comparison

X+			X0		
SC	PSCAD	LIV	SC	PSCAD	LIV
0.01013	0.0098	0.0099	0.0337	0.0345	0.0330

Unbalanced Mutual Impedance Impacts on 765kV Line Apparent Impedance Calculation

Most AEP 765kV transmission lines are not transposed and mutual impedance unbalance is severe enough to impact the apparent sequence network impedance estimation. In this section, statistics of AEP 765kV transmission line-apparent impedance deviations for different types of faults will also be presented. This statistical analysis addresses the reasonable error range that LIV may incur and an explanation of the error range.

After modeling all AEP 765kV transmission line in PSCAD and estimating apparent impedance using AG, BG, and CG faults, respectively, deviations of estimated apparent positive and zero sequence apparent reactance for different types of fault are calculated. Deviation defined in (4) is used for comparison and the variation in percentage is in Figure 4.

$$dev_{YG} = \frac{X_{YG} - (X_{AG} + X_{BG} + X_{CG})/3}{(X_{AG} + X_{BG} + X_{CG})/3} \qquad (4)$$

where X_{YG} is the estimated reactance from phase Y to ground fault. Y could be replaced by A, B, or C to represent corresponding phase to ground faults. Both positive sequence reactance deviations and zero sequence reactance deviations are calculated in this analysis.

It is well known that a BG fault would deviate from an AG and CG fault. However, an AG fault estimated apparent impedance also deviates from a CG fault estimated apparent impedance. And up to 5% of the variations are observed from the statistical results as shown in Figure 4. Hence the type of fault used for model validation should be selective, even for edge phase to ground fault.

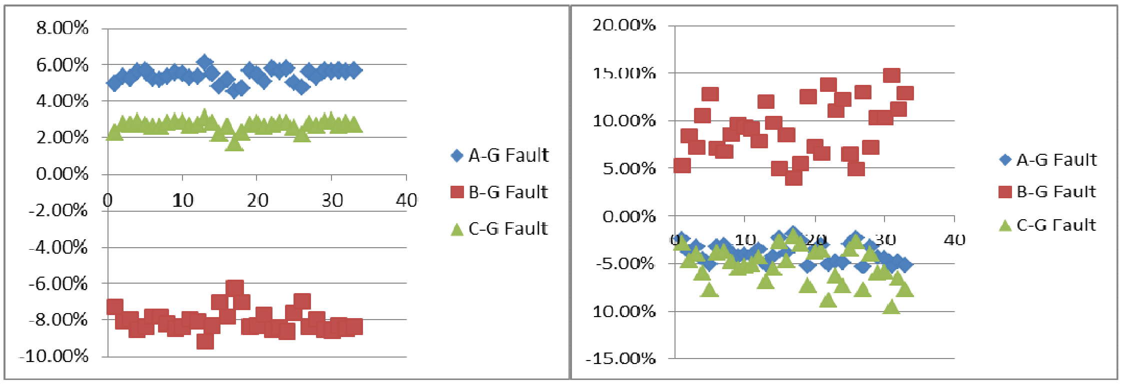

Figure 4 AEP 765kV Line Pos. (Left) and Zero (Right) Seq. Reactance Variations

AEP 765kV Line Apparent Impedance Validation

A. AEP 765kV Line Distance Relay Setting Criteria

Due to the significant impact of mutual couplings between the phases of a 765kV untransposed line during a fault, the apparent impedances calculated by a short circuit simulation software using sequence network PI-model do not match the actual impedances measured by a relay. As a result, zone distance settings for the 765kV line should not be based on the line impedances (or apparent impedances) derived from the short-circuit model. Instead, EMTP/EMTDC transmission line models, including self-mutual coupling effects, should be used to simulate a fault, calculate the apparent impedances, and set the relay zone distance elements accordingly. In addition, the distance zone elements in the relay should be set according to the apparent impedance of the worst case scenario. For instance, Zone 1 of a distance relay should be set based on the smallest apparent impedance measured by the relay for a remote bus fault. On the other hand, Zone 2 and Zone 3 should be set based on the largest apparent impedance measured by the relay for a remote bus fault or for a breaker failure condition. When calculating apparent impedances for zone distance settings, four fault scenarios, i.e., the three-phase fault (ABC-G) and three phase-to-phase faults (AB-G, BC-G, AC-G), are simulated and corresponding phase-to-phase apparent impedances (Zab, Zbc, Zac) are calculated. Then Zone 1 is set based on minimum (Zab, Zbc, Zac) with a margin (under-reach), and Zone 2 and Zone 3 are set based on maximum (Zab, Zbc, Zac) with a margin (over-reach).

B. AEP 765kV Line Apparent Impedance Validation

The PSCAD-based apparent impedance calculation model is presented in Figure 5. The apparent impedances calculated by the PSCAD model are compared with benchmark apparent impedances calculated by a line constant tool. Table II shows the impedance differences calculated by the two different models. The apparent impedance differences from the PSCAD model are less than 3%, so the PSCAD model is accurate enough for calculating apparent impedances.

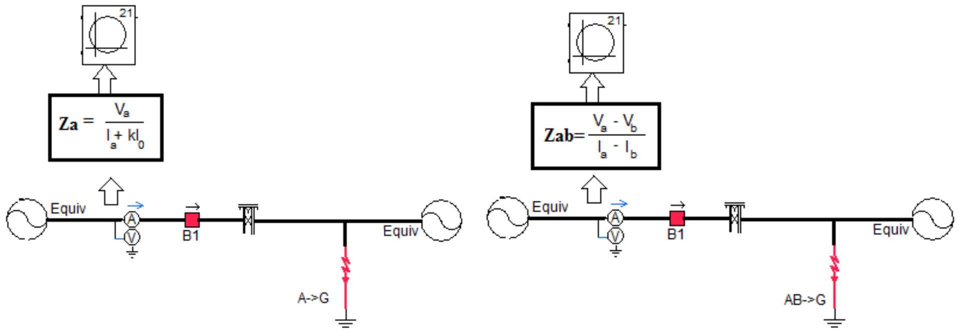

Figure 5 SLG (Left) and LLG (Right) Impedance Validation Simulation

Table II Line-to-Line Apparent Impedance Validation

LL	Benchmark		PSCAD		Δ%
	X	Zpri	X	Zpri	
Zab	55.39	55.41	56.68	56.82	2.5%
Zbc	55.77	55.8	54.89	54.9	-1.6%
Zac	64.31	64.35	64.83	64.87	0.8%

Conclusions

Existing short-circuit calculation tools or load flow models are based on a three-phase symmetry system and are not able to evaluate the system unbalance due to untransposed EHV transmission lines. In this paper, an EMTP/EMTDC type transmission line model for AEP 765kV untransposed system is developed in PSCAD and the estimated apparent impedances are validated by fault records. Through the validation process, limited types of fault records could be used to validate the accuracy of the PSCAD model and the various types of fault simulation on the validated model could provide a more detailed set of apparent impedances as seen by the relay. Furthermore, 765kV transmission system PSCAD model could also be used in system unbalance studies, three-phase power flow studies, and other EMTP/EMTDC type studies. The effect of the unbalanced self-mutual coupling on apparent impedance calculation is also analyzed.

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