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Sensitivity Analysis for Influential Parameters in Simulations of Induced Voltage between Close Proximity AC Transmission Circuits

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SUMMARY

In the United States, there are millions of miles of double-circuit EHV transmission lines on shared structures. A benefit of double-circuit lines is that line maintenance work can be performed on a de-energized circuit while the other circuit remains energized. However, induced voltages can be generated on the de-energized line due to electrostatic effects and the close proximity to energized conductors. OSHA requires using temporary protective grounds (TPGs) to ensure worker safety. Installation of TPGs on the de-energized line will generate induced currents in the de-energized circuit as a result of magnetostatic coupling with the energized circuit. Arcing can occur while removing each TPG and create safety concerns. In order to mitigate this safety concern, grounding switches may be installed. This can be an expensive solution for EHV lines. As a result, the magnitude of induced voltage and current is the key for defining safety criteria to judge whether or not a costly mitigation plan is needed. This paper focuses on the sensitivity analysis of induced voltage parameters to distinguish the highest-impact factors. With this effort, the calculation of induced voltages can be more efficient and achievable as a complete model of all parameters may be difficult to obtain. In addition, this paper can provide a guideline for engineers who design a double-circuit line to know which physical and electrical parameters may have the greatest effect on the induced voltages.

KEYWORDS

Induced Voltage, Sensitivity Analysis, Influential Parameters, Simulation

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INTRODUCTION

Double-circuit lines offer redundancy and reliability. If installed on the shared transmission towers the right of way can also be minimized. A great benefit of double-circuit lines is that one circuit can remain in service while the second circuit can be de-energized for line maintenance.

Temporary protective grounds (TPGs) are typically used for de-energized transmission line work according to OSHA rules [1]. Installation of TPGs causes induced currents in the de-energized line when in close proximity to an energized line. The first TPG installed causes a relatively small current to flow in the de-energized line due to the capacitive coupling of the de-energized line to the energized line. The second TPG installed creates a magnetically induced loop current that is proportional to the length of the loop (between TPGs) and the magnitude of the load current in the energized line. The distance between two TPGs is typically a span (less than 0.3 mile) and thus is assumed to be relatively small.

In addition, the removal of TPGs (arc interruption) presents greater challenges than TPG installation (pre-arcing) due to the effects of air ionization and plasma behaviour. As a result, the severity of the arc associated with removing the TPG is directly related to the magnitude of the recovery voltage. The recovery voltage is equal to the induced voltage present due to electrostatic coupling from the energized line. Removing the last TPG (Fig. 1) on the de-energized circuit should cause the most severe arc, as the maximum recovery voltage occurs once the de-energized conductor is floating. The induced voltage between the floating de-energized line and the ground is simply referred as “induced voltage” in the remainder of this work.

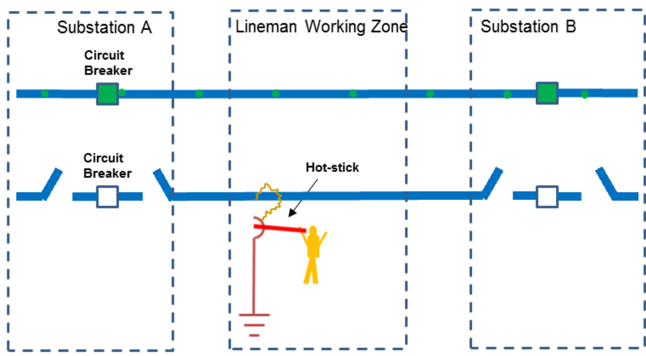

Figure 1. Using hot-stick to remove the last TPG from a de-energized line

There has been previous research on this topic. Horton published a transaction paper in 2008 with a detailed introduction of induced voltage and current causes and concerns [2][3]. Horton presented a method using WinIGS to simulate line coupling and compared the results with field measurements. Mousa used some calculations and analysis to propose a new grounding procedure for TPGs, which has influenced current OSHA rules for more than thirty years [4]. In addition, we presented a paper regarding the induced voltage and current calculation formulas and simulation strategies for fully or partially parallel scenarios [5].

However, none of the above listed references provide general guidelines of how induced voltages are impacted by physical line and tower designs. In order to accurately and efficiently calculate the induced voltage magnitudes, an induced voltage sensitivity analysis is needed. Additionally, this is the first step to creating design guidelines to avoid or mitigate high induced voltages on double-circuit lines.

SENSITIVITY ANALYSIS

In the real-world application, there are multiple factors influencing the induced voltage magnitudes on the de-energized line in close proximity with energized circuits. Theoretically, the most important factors are voltage magnitude of the energized circuits and separation distance between de-energized and energized circuits. In addition there are many other factors that are difficult to collect or model with accuracy such as soil resistivity, tower footing resistance, and conductor/shield sag. To further complicate issues, tower configurations and conductor materials may be different in the same circuit. As a result, there are many uncertainties in the induced voltage calculations for existing circuits. It is necessary to compare those factors between each other and clearly define high and low impact factors. Thus, a more accurate induced voltage calculation is achievable, and would help engineers design a circuit and tower arrangement to minimize induced voltage levels.

A sensitivity analysis using a one-factor-at-a-time (OFAT) approach is used to determine the impact level when many factors are considered. Typically, a standard combination of all factors is defined, and then for each scenario one factor is changed while all other factors remain the same. Note that partially parallel scenarios are included in the analysis, which specifically relates to the percentage of total length that the circuits are in parallel.

The standard line configuration modeled in CDEGS [6] is shown in Fig. 2 and Fig. 3. The energized circuit voltage and current are defined as 345 kV (line-to-line rms) and 100 Amps, respectively. The tower footing resistance used is 15.4 Ω with a buried 20 foot long, 2 inch diameter ground rod.

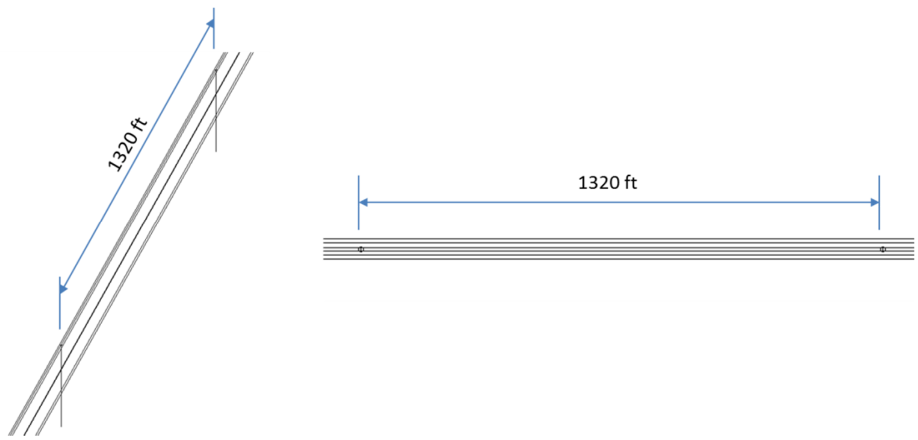

Figure 2. Standard model illustration (isostatic and top view)

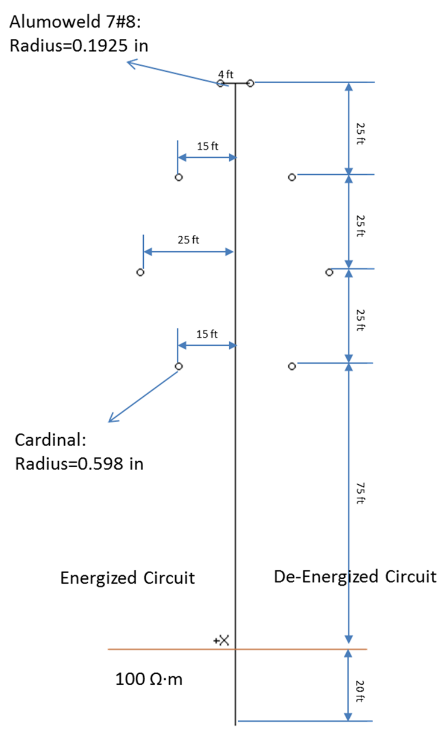

Figure 3. Standard model illustration (section view)

Since a lattice tower is usually difficult to model precisely in the software and time-consuming for the calculations, the difference between the simplified model (shown in Fig. 3 as a long vertical rod) and a true lattice tower (as shown in Fig. 4) is analyzed

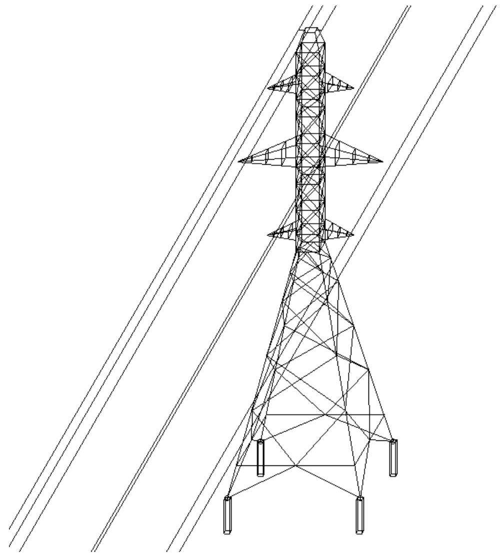

Figure 4. Complex tower model illustration

An example of partially parallel case modeled in CDEGS is shown in Fig. 5. Both circuits have the same total length and the percentage of line length in parallel varies for each simulation scenario. As shown the lines are parallel at one end and remain parallel until one line diverges at a 45°.

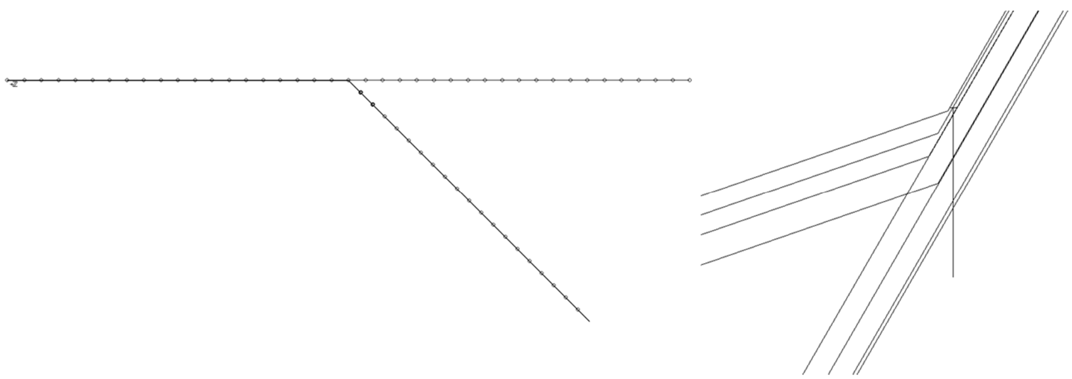

Figure 5. Partially parallel case model illustration

In addition to physical design and electrical parameters (i.e. energized circuit voltages and currents), different materials and soil resistivity are studied as well. Tables 1 through 17 show the sensitivity analysis results of 17 influential factors.

Table 1 Energized Circuit Voltage Impact

Energized Circuit Voltage Class (kV)	138	230	345
Top Phase (V)	5446	9078	13616
Middle Phase (V)	1074	1794	2694
Bottom Phase (V)	6077	10133	15201

Table 2 Energized Circuit Current Impact

Energized Circuit Voltage Class (A)	100	200	300
Top Phase (V)	13616	13613	13615
Middle Phase (V)	2694	2688	2683
Bottom Phase (V)	15201	15192	15190

Table 1 shows that induced voltage is directly proportional to the energized circuit voltage. In contrast, the energized circuit load current has negligible impact on the induced voltage (as shown in Table 2). This is expected as the induced voltage is due to electrostatic coupling and not magnetostatic coupling. The small differences between induced voltage magnitudes as load current changes are due to voltage drop across the conductor.

Table 3 Soil Resistivity Impact

Soil Resistivity (Ω·m)	20	100	500
Top Phase (V)	13620	13616	13614
Middle Phase (V)	2695	2694	2694
Bottom Phase (V)	15206	15201	15201

Table 3 shows the induced voltage changes due to soil resistivity are negligible. It is reasonable because the induced voltage is calculated based on the capacitive division between the line coupling and the ground coupling, and the mutual/self-capacitance is independent of the soil resistivity [3][5]. Considering the typical soil conditions across the AEP system, a resistivity of 100 Ω·m is a reasonable approximation.

Table 4 Energized Line Size Impact

Energized Conductor Material (Radius)	Raven (0.199 in)	Bluebird (0.881 in)
Top Phase (V)	11614	14496
Middle Phase (V)	2083	2979
Bottom Phase (V)	13005	16163

Table 4 indicates a larger conductor radius in the energized line(s) leads to a greater induced voltage. When a circuit consists of multiple line types, using the largest-radius conductor is more conservative approach for simulations.

Table 5 Shield Wire Size Impact

Shield Wire Material (Radius)	OPGW 48 (0.3185 in)	Alumoweld 7#10 (0.153 in)
Top Phase (V)	13320	13744
Middle Phase (V)	2663	2712
Bottom Phase (V)	15285	15165

Table 5 shows the shield wire size is not an influential factor, which can be generically estimated.

Table 6 Number of Shield Wire Impact

Shield Wire #	1	2
Top Phase (V)	15929	13616
Middle Phase (V)	3274	2694
Bottom Phase (V)	14533	15201

Table 6 shows that a single shield wire arrangement leads to larger induced voltage than a two shield wire arrangement. This is expected as electrostatic coupling with ground is reduced with a single shield wire. This suggests that including two shield wires in a double-circuit line design can reduce induced voltage by 15%~20%.

Table 7 Shield Wire Height Impact

Shield Wire Height (ft)	140	150	160
Top Phase (V)	10944	13616	15400
Middle Phase (V)	2617	2694	3079
Bottom Phase (V)	15785	15201	14795

Table 8 Shield Wire Horizontal Spacing Impact

Shield Wire Spacing (ft)	2	4	6
Top Phase (V)	13940	13616	13471
Middle Phase (V)	2741	2694	2679
Bottom Phase (V)	15101	15201	15256

Table 7 illustrates that the induced voltage on the top phase is impacted by the vertical distance from the shield wire(s). However, the horizontal spacing between two shield wires does not have a large impact and can be neglected (as shown in Table 8).

Table 9 Tower Footing Resistance Impact

Tower Footing Resistance (Ω)	11	15.4	19.6	27.4
Top Phase (V)	13617	13616	13616	13615
Middle Phase (V)	2694	2694	2694	2694
Bottom Phase (V)	15200	15201	15201	15202

Table 9 shows the tower footing resistance can be generically estimated, a resistance of 15 Ω is suggested as a practical value. Note that the reason of its very small impact is similar with the explanation under Table 3.

Table 10 Bottom Phase Height Impact

Tower Height (ft)	55	65	75	85	95
Top Phase (V)	14279	13914	13616	13369	13159
Middle Phase (V)	2508	2538	2694	2897	3109
Bottom Phase (V)	13198	14331	15201	15891	16451

Table 10 demonstrates the impact of tower height while the phase conductor configuration is unchanged. As the height increases the bottom phase induced voltage increases as the electrostatic coupling with ground is reduced. However, the top phase induced voltage decreases as the tower height increases.

Table 11 Horizontal Distance between Circuits Impact

Circuit Horizontal Spacing (ft)	15	19	23	27	35
Top Phase (V)	13616	11597	10009	8752	6950
Middle Phase (V)	2694	2767	2784	2766	2676
Bottom Phase (V)	15201	12897	11006	9438	7021

Table 11 shows the horizontal spacing between two circuits significantly influences the induced voltage. As the spacing increases, the mutual electrostatic coupling between two circuits is reduced and the induced voltage decreases.

Table 12 Phase Conductor Vertical Spacing Impact

Phase Conductor Vertical Spacing (ft)	15	20	25	30	35
Top Phase (V)	10721	12179	13616	14607	14996
Middle Phase (V)	6303	4657	2694	635	1738
Bottom Phase (V)	11304	13187	15201	16975	18373

Table 12 indicates that the induced voltage decreases as the vertical spacing between phases is reduced. This is due to increased electrostatic cancelling of adjacent phases in a more compact configuration. As the conductors become more spread out the net electrostatic coupling will increase leading to higher induced voltages.

Table 13 Top/Bottom Phase Horizontal Spacing Impact

Top & Bottom Phase Horizontal Spacing	10 ft	12.5 ft	15 ft	17.5 ft	20 ft
Top Phase (V)	22418	17337	13616	10851	8804
Middle Phase (V)	5164	3921	2694	1483	290
Bottom Phase (V)	24621	19269	15201	12035	9554

Table 13 shows the induced voltage change when the top and bottom phase spacing increases. In this case the middle phase remains 25 ft away from the structure. As the distance from the energized conductors increases the induced voltage is lower. Additionally, when a de-energized line is equidistant from all three phases the electrostatic coupling effect can be significantly canceled out (i.e. middle phase induced voltage in one scenario has a magnitude of only 290 V).

Table 14 Span Length Impact

Span Length (ft)	660	1320	2640
Top Phase (V)	13603	13616	13616
Middle Phase (V)	2678	2694	2696
Bottom Phase (V)	15203	15201	15202

Table 14 illustrates that the span length (between two structures) does not greatly influence the induced voltage and can be generically estimated.

Table 15 Conductor Bundling Impact

Bundled	No	Yes (2 conductors)
Top Phase (V)	13616	19159
Middle Phase (V)	2694	4412
Bottom Phase (V)	15201	21242

Table 15 shows the bundled phase conductors lead to larger induced voltages. Hence the conductor bundling should be verified prior to simulation.

Table 16 Modeled Tower Complexity Impact

Tower Complexity	Simplified	Complex
Top Phase (V)	13616	12579
Middle Phase (V)	2694	2472
Bottom Phase (V)	15201	13833

Table 16 shows that modeling a more complex structure will reduce the induced voltage output. However, it is unrealistic to model the tower like Fig. 4 for a long right-of-way due to long software runtime. A simplified model can be used as a conservative option.

Table 17 Percentage in Parallel Impact

Percentage in Parallel	100%	75%	50%	25%
Top Phase (V)	13616	10265	6894	3480
Middle Phase (V)	2694	2086	1473	769
Bottom Phase (V)	15201	11419	7636	3834

Table 17 shows the percentage of total line length in parallel is directly proportional to the induced voltage. Hence, the line routing and any divergence between lines should be accurately modeled.

Table 18 Summary of Parameters and Impact Level

Parameters	Impact Level
Energized Circuit Voltage	High
Energized Circuit Current	Low
Soil Resistivity	Low
Energized Conductor Size	Middle
Shield Wire Size	Low
Number of Shield Wire	Middle
Shield Wire Height	Middle
Shield Wire Horizontal Spacing	Low
Tower Footing Resistance	Low
Tower Height (Bottom Phase Height)	Low
Horizontal Distance between Circuits	High
Vertical Distance between Circuits and Shield Wires	Middle
Phase Conductor Vertical Spacing	Middle
Top/Bottom Phase Horizontal Spacing	High
Span Length	Low
Conductor Bundling	High
Modeled Tower Complexity	Middle
Percentage in Parallel	High

Table 18 lists the impact levels (high, middle, and low) for all analyzed parameters. All of the high-impact parameters should be accurately represented when a simulation is conducted; whereas the low-impact factors can be neglected or generically estimated.

CONCLUSIONS & FUTURE WORK

This paper presents a sensitivity analysis of 17 different factors relating to induced voltage in double-circuit lines installed on shared structures. Using these results, a complicated induced voltage simulation can be simplified by focusing on the high-impact parameters and estimating the low-impact parameters. Thus, the simulation will be more accurate and efficient. Additionally, design and planning engineers can use these recommendations at the design stage to avoid high induced voltages, as well as mitigate induced voltage issues.

Future work needs to be done to develop a better model for arc behaviour as well as develop safety criteria for removal of TPGs using a hot-stick. Further mitigation methods (such as line grounding switches) may be necessary if this work cannot be performed using these safety criteria. In addition, induced voltage field measurements are being recommended within AEP's footprint in the near future, which will provide further validation of electrostatic coupling simulations.

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