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Resonances, Safety And Parallel Transmission Lines

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SUMMARY

An energized circuit with electric and magnetic fields can induce voltage and current in a de-energized transmission line that is in the vicinity. Very high overvoltages or high currents may appear on the "de-energized" transmission line if it is compensated with shunt reactors or series capacitors. Also, ferroresonance may appear on the "de-energized" transmission line if it contains nonlinear shunt reactors or transformers.

These voltages and currents may present equipment damage and / or work hazard for line-crew personnel. The Occupational Safety and Health Administration (OSHA) requires temporary protective grounds (TPG) whenever work is performed on de-energized transmission lines where induction hazard could exist [1]. However, during connecting or disconnecting the TPGs, if the induced currents and/or voltages are large, very long arcs may occur which could be lethal. The induced current may be very high, particularly for series capacitor compensated lines.

Parallel transmission lines are quite prevalent in power systems. In March of 2009 the Public Utilities Commission of Texas (PUCT) issued the final order for the Competitive Renewable Energy Zone (CREZ) to ultimately interconnect approximately 18.5 gigawatts of renewable generation in West Texas to loads centers in Central Texas. The initial CREZ project consists of over 1200 miles of double circuit 345 kV transmission lines. Dispersed across CREZ transmission lines are sixteen 345 kV series capacitors, and several shunt reactors.

This report demonstrates the possibilities for the high induced voltages, resonances and ferroresonance and induced currents in "de-energized" transmission lines, that are in the vicinity of energized transmission lines. The principle of induced resonance/ferroresonance voltages and currents are presented. Study results and field events are provided. A unique ferroresonance mitigation technique that has been implemented at AEP is described. Personal safety issues due to the induced voltages and currents are discussed.

KEYWORDS

Resonance – Ferroresonance – Series Capacitors - Double Circuit - Parallel Transmission Lines –Electromagnetic – Coupling – Live Line Work.

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1. PRINCIPLES

The electrostatic, the electromagnetic and the resonances can be explained by considering a double circuit or the parallel portion of two transmission lines. Circuit I is energized and Circuit II is opened. To simplify the analysis, only phase (A) of the Circuit I and Circuit II is demonstrated.

1.1 ELECTRICSTATIC COUPLING

The electrostatic or the capacitive coupling can be demonstrated by Fig.1. The $Z_{C(Aa)}$ is the capacitive impedance between Circuit I and Circuit II and $Z_{C(ag)}$ is capacitive impedance to ground for Circuit II.

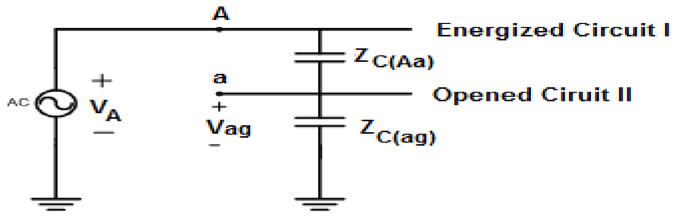


Fig. 1. Capacitive coupled circuit representation of two parallel circuits.

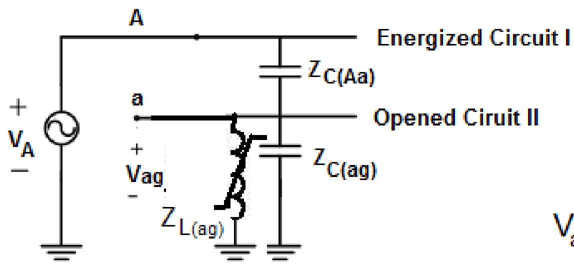
The voltage induced into conductor (a) due to a voltage being applied to conductor (A) can be calculated using the following voltage division [1,3,4]:

$$V_{ag} = V_A \times Z_{C(ag)} / (Z_{C(ag)} + Z_{C(Aa)}) \quad (1)$$

Note that in the above expression, the steady state induced voltage V_{ag} is less than the source voltage V_A. The total V_{ag} can be obtained by adding to (1), similar ratios for the coupling from phase (B) to phase (a), and from phase (C) to phase (a).

1.2 RESONANCE

Now, assume that the opened Circuit I is compensated with a shunt reactor (Fig. 2), having inductance L_{ag}. Then $Z_{C(ag)}$ in the expression (1) represents the parallel impedances due to C_{ag} and L_{ag}. And, the expression (1) changes to:



$$V_{ag} = V_A \times C_{Aa} / [(C_{Aa} + C_{ag}) - 1/(\omega^2 L_{ag})] \quad (2)$$

Fig. 2. Capacitive coupled representation, with shunt compensation.

In the above expression, the induced voltage V_{ag} can be much larger than the source voltage V_A if the denominator becomes smaller than the numerator. Again, the total V_{ag} can be obtained by adding to (2), similar ratios for the coupling from phase (B) to phase (a), and from phase (C) to phase (a).

1.3 FERRORESONANCE

The Ferroresonance is a type of resonance involving a capacitance in series with a nonlinear inductance. The ferroresonance oscillations can be periodic, quasi periodic or chaotic. The key features are existence of several different steady state conditions. And, small perturbations or parameter change can cause jumps from one state to another or back to a

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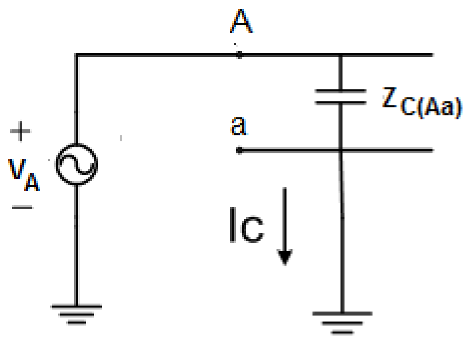
non-resonant condition. Many aspects of ferroresonance have been covered in the literature and the reference [4] presents a comprehensive summary.

The necessary but not sufficient conditions for ferroresonance are the existence of open or very lightly loaded conditions (such as isolated neutral, single fuse blowing, opened phase(s), etc.). Fig. 2 shows the possibility of ferroresonance in the opened circuit, by the capacitor $C_{(Aa)}$ and $L_{(ag)}$, assuming that $L_{(ag)}$ represents a nonlinear shunt reactor or an unloaded transformer. In a later section of this paper a field event and a special mitigation for this condition is presented.

1.4 CAPACITIVE CURRENT

No longer would the open conductors have significant voltages, once the “de-energized” circuit is grounded, Fig. 3. And, there is a path for charging current to flow. The magnitude of the current I_c, due to the energized phase (A) only, is:



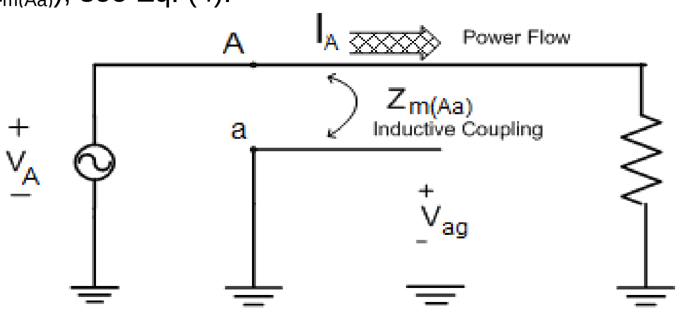
$$I_C = 377\ C_{Aa} V_A \qquad (3)$$

Fig. 3. Coupled Charging Current

The total I_c can be obtained by adding to (3), similar expressions for the coupling from phase (B) to phase (a) (i.e. $377\ C_{Ba}\ V_B$), and from phase (C) to phase (a) (i.e. $377\ C_{Ca}\ V_C$).

1.5 ELECTROMAGNETIC COUPLING

Current flow in the energized conductor due to load or short circuit produces a magnetic field (see Fig. 4) that links the open conductor (a) in the vicinity [1]. The magnetic field induces a voltage “along” the open conductor (a). If one terminal of the open conductor is shorted to ground, then the electromagnetic induced voltage along the line is equal to the open terminal voltage, with respect to ground. The magnitude of this voltage is a function of the current flowing in the energized conductor (I_A), and the mutual impedance between the lines (s.a. $Z_{m(Aa)}$); see Eq. (4).



$$V_{ag} = Z_{m(Aa)}\, I_A \qquad (4)$$

Fig. 4. Magnetically coupled circuit representation of two parallel circuits.

If a second short is added to the open terminal, current I_a can flow due to electromagnetic coupling (see Fig. 5). The magnitude of the current I_a is as follow.

$$\mathbf{I_a = -\ I_A\ Z_{m(Aa)} / Z_{aa}} \qquad (5)$$

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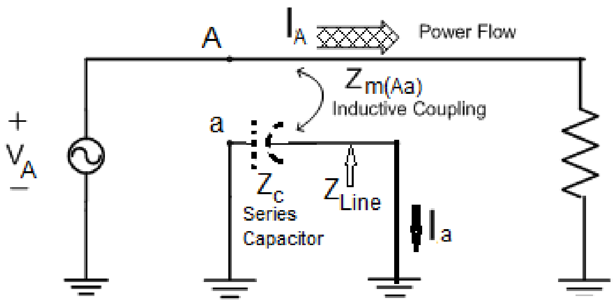
Where, Z_{aa} is the impedance of the loop that is created by the two shorts [2]. The electromagnetically induced current either adds or subtracts from the electro statically induced current. Note that adding series capacitor compensation to the lines, will change Z_{aa} to ($Z_{aa} = Z_{Line} - Z_C$) and will increase electromagnetically induced current, considerably.



$$I_a = - I_A Z_{m(Aa)} / (Z_{Line} - Z_C) \qquad (6)$$

Fig. 5. Electromagnetically induced current flow.

2. SAFETY ISSUES FOR LINE WORKERS

Generally, the majority of the current through single temporary protective grounds (TPG) on the line is due to the electrostatic coupling. And, the current through two TPG's is due to electromagnetic field. Many of the workers accident occur during connection or removal of the TPG, when very long arcs may appear. The induced current due to the capacitance or magnetic could be dangerous to line workers if accidently they would be at the current path. The dangerous body current levels are beyond "let-go" threshold of 10 mA or beyond ventricular fibrillation threshold level of 60 to 100 mA [Ref]. The workers should be cautious during this process and must adhere to the OSHA 1910.269 rules of "order of connection" and "order of removal," [1, 6].

3. CASE STUDIES AND EVENTS

As was mentioned earlier, the CREZ system includes 1200 miles of double circuit transmission lines. American Electric Power (AEP), join ventured with MidAmerican Energy Holdings Company, will construct approximately 400 miles of CREZ double circuit 345 kV transmission lines. This portion include 8 series capacitor banks and eighteen 50 MVar shunt reactors. Also, in the AEP system there are many other parallel transmission circuits that include transformers. This section provides case studies for the induced voltage/resonance and induced current levels for the AEP segment of the CREZ transmission lines. Also described are AEP ferroresonance events and the applied mitigation technique.

A number of 345 kV double circuit transmission lines were properly simulated using the PSCAD program. The conductors of the circuits are in vertical configurations with the low reactance phasing. The PSS/E and ASPEN databases were used for representing the system at the line terminals and ensuring proper load flow and short circuit levels for each of the simulated double circuit lines. A very large number of cases with a variety of conditions were simulated. The more interesting results are the induced voltages and resonances with one of the double circuit line (Fig. 6 and Table 1) and the induced currents in another double circuit line (Fig. 7 and Table 2).

3.1 INDUCED AND RESONANT VOLTAGE

The induced and resonant voltage levels depend on the tower and line geometry and on the presence of shunt reactors and the line terminal surge arresters. The phase conductors in the double circuit line are in vertical configuration and the line is not transposed. Thus coupling between phases are not equal and the induced voltages have different values in the

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three phases of the open circuit. Table 1, case 1 shows the maximum induced voltage is 23 kV, without shunt reactors. The line is about 90% compensated with the 50 MVar shunt reactor bank. This results in a resonant voltage of 450 kV in the open circuit, when shunt reactors are in service (case 2). The resonant voltage is up to 2.85 MV if only one phase of the double circuit is opened (case 3). The presence of the 258 kV rated surge arresters at the line terminals reduce cases 2 and 3 voltages to 302 and 312 kV, respectively. With these levels the arresters' energy dissipation would exceed the capability in less than 2 seconds. Inclusion of corona or the reactor nonlinearity in the simulations would alter the values, however voltages would remain large and may damage equipment and may be of safety concern for live line work.

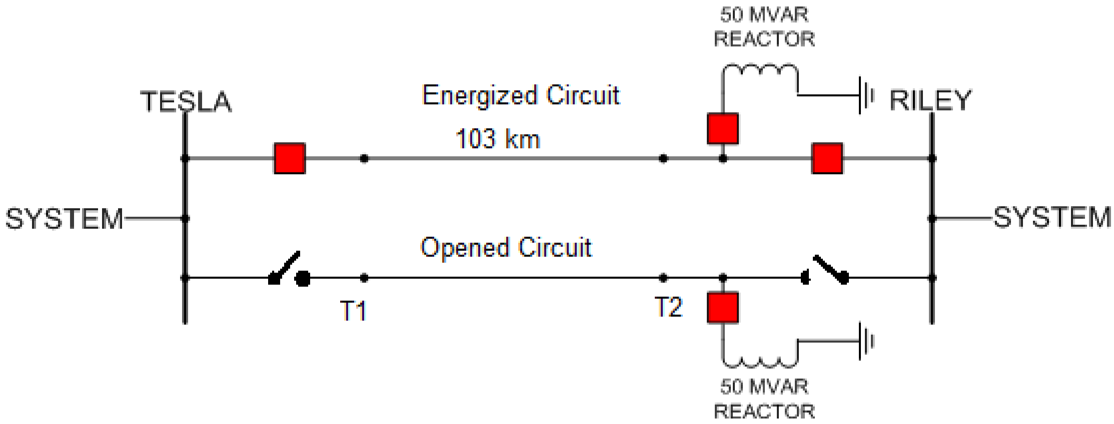

Fig. 6. Simplified one-line diagram of the Tesla – Riley 345 kV line

Table 1. Maximum Induced and Resonance Voltages for the Tesla–Riley 345 kV line

Case	Number of phases opened	Description	Without Surge Arresters (kV-rms)	With Surge arresters (kV-rms)
1	3	Induced (Without Shunt Reactor)	23	NA
2	3	Resonance (With Shunt Reactor)	450	302
3	1	Resonance (With Shunt Reactor)	2,850	312

3.2 INDUCED CURRENT

The induced current depends on the power flow, presence of series capacitors and faults. Again, the induced currents are different in the three phases. Table 2, corresponding to Fig. 7, shows the maximum induced current at the shorted terminals for various grounded locations. The voltage at the open terminal is also presented when only one terminal is grounded.

The series impedance of the line is about 50% compensated by the 24 Ohms capacitors. It is interesting to note that when both terminals are grounded, the presence of the series capacitor increases the induced current from 62 A (case 3) to 104 A (case 4) or to 560 A (case 6) for a ground next to the capacitor. It is also interesting to note that with grounds at the terminals and a bus fault, the induce current increases to 807 A (case 5). And with a ground next to the capacitor (S2) and at terminal T1, the induce current increase to 5138 A (case 7). Such information can be used to ensure proper capability of ground switches and to ensure proper practice by the live line personnel when using Temporary Protective Grounds.

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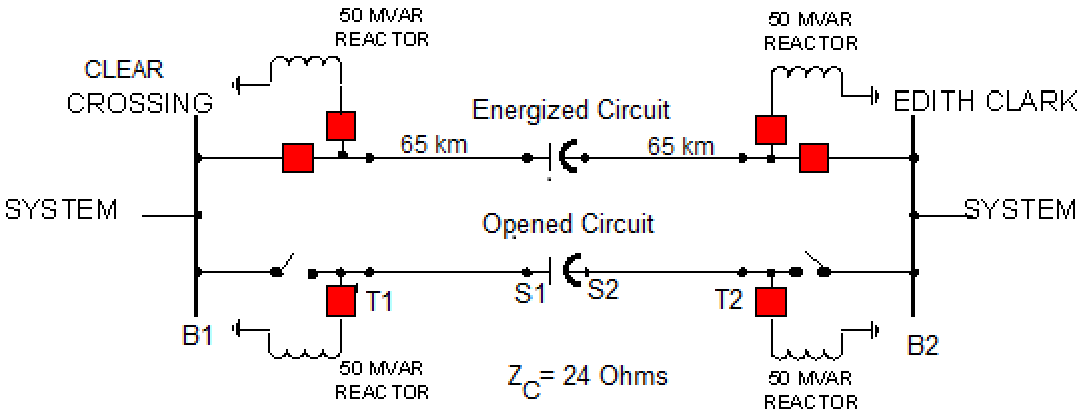

Fig. 7. Simplified one-line diagram of the Clear Crossing – Edith Clark 345 kV line

Table 2. Maximum Induced Current for the Clear Crossing – Edith Clark 345 kV line

Case	Grounded Locations	Current to Ground at Line Terminal (A-rms)	Voltage at Open Terminal (kV-rms)
1	T1	11	3
2	T1+B2	9	24
3	T1+T2+ without Zc	62	NA
4	T1+T2	104	NA
5	T1+T2+B2	807	NA
6	T1+S2	650	NA
7	T1+S2+B2	5138	NA

3.3 FERRORESONANCE

Figure 8 shows the American Electric Power Cook-Robinson Park 345 kV circuits. There is a 345/138 kV transformer at East Elkhart and another at Kenzie Creek. At two separate occasions when the line, associated with a transformer and the low side of the transformer opened, ferroresonance occurred. This was evident by the transformers unusual humming sounds, and relays chattering which in one case lasted over 5 hours. The Data Acquisition System recorded voltage variation between 11 to 81 percent of the nominal voltage at E.

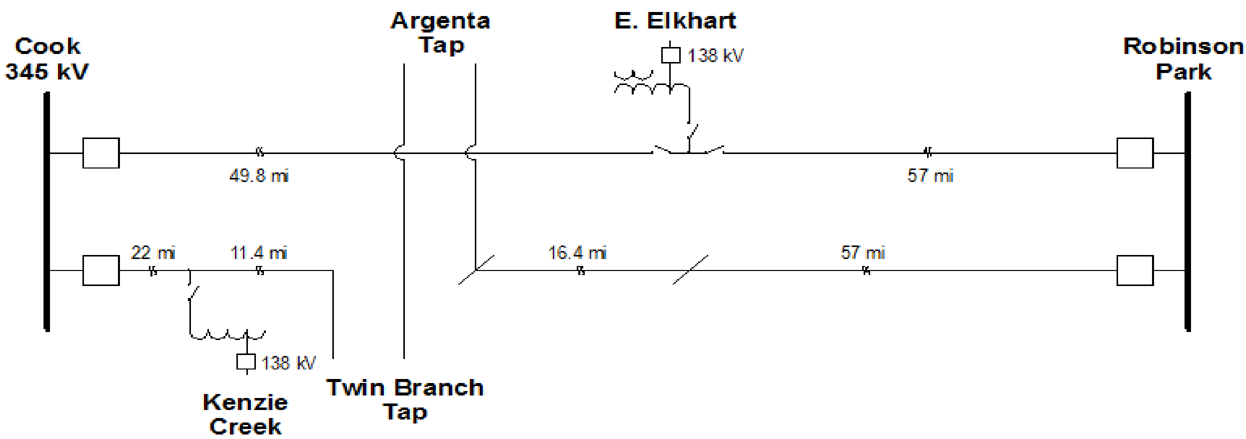

Fig. 8. Simplified one-line diagram of the Cook-Robinson Park 345 kV Circuits..

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Elkhart and 20 to 50 percent for Kenzie Creek transformer. Fig. 9 shows the recorded waveform for the Kenzie Creek event. In each case the opened line was re-energized and opened again. The ferroresonance did not reappear, since the sequence of opening was different.

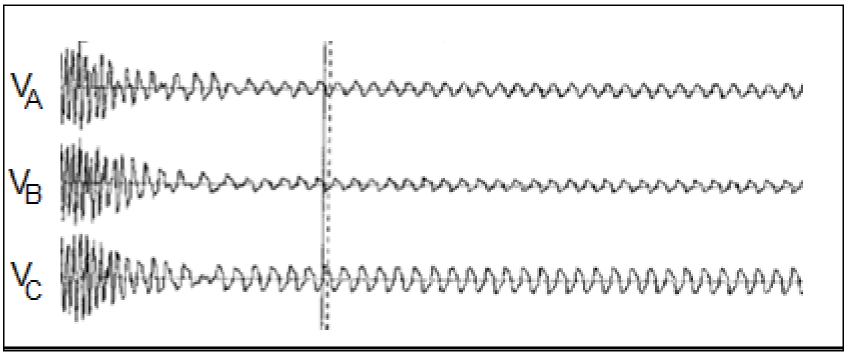

Fig. 9. Field recorded ferroresonance, 345 kV voltage waveform, for opening Cook-Twin Branch circuit.

The computer analysis verified the ferroresonance (FR) phenomenon. The FR was initiated due to 1) the line opening in a particular phase sequence, 2) capacitive coupling from the energized circuit to the opened circuit, 3) the opened circuit capacitance to ground, and 4) the nonlinear impedance of the E. Elkhart transformer.

Various options for avoiding the FR were considered. The options included:

1. A circuit breaker or circuit switcher on the 345 kV side of the transformers.
2. Open the existing MOAB at the high side of the transformers, after the associated line is "de-energized."
3. Add load (the larger the better) to the transformer, prior to doing the step 2.
4. Add a filter to the transformers' tertiary to damp the resonance
5. Add a three phase grounding switch to the transformers' tertiary, prior to doing step 2, above. Grounding switch would open, after the MOAB is opened.
6. Change the FR circuit parameters by changing the position of the phases.

The option 6 was selected due to the cost and the ease of implementation. For E. Elkhart transformer, for example, the position of the top and bottom phases at Cook and at E. Elkhart terminals of the circuit were switched. This way, the 50 miles between Cook and E. Elkhart was low reactance phasing (from top to bottom: A-B-C on one circuit and c-b-a, on the other). The other section of the line (55 miles between E. Elkhart and Robison Park) remained in superbundle phasing (from top to bottom: A-B-C on one circuit and a-b-c, on the other also).

As mentioned earlier, a small parameter change can cause jumps from one state to another or back to a non-resonant condition. By making about "half of the line" low reactance and the "other half" super bundle, the steady state coupling from the energized circuit to the opened circuit was reduced to 11 kV (from 22 kV, previously). The computer analysis and the subsequent field tests verified that this reduction avoided a ferroresonance occurrence.

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4. CONCLUSIONS AND RECOMMENDATIONS

Resonances and safety issues associated with the parallel transmission lines are presented in this paper. An opened transmission circuit in the vicinity of an energized circuit may be exposed to very large voltages and /or currents. The levels of the voltages and currents depend on the circuits' geometry, series capacitor compensation, nonlinear shunt reactors or transformers, system parameters and the presence of shorting switches or the temporary protective grounds. Ferroresonance events are described for parallel circuits when one circuit having a transformer opens. A unique ferroresonance mitigation technique, applied in the field, is described. The principles and parameters presented in this paper can be used to decide on a) proper protective equipment, such as grounding switches or the temporary protective grounds, b) control strategies, such as shorting series capacitors, opening shunt reactors or transformers when one circuit is opened and c) the safe practices during the live line work.

ACKNOWLEGEMENT

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REFERENCES

[1] R. Horton, K. Wallace, "Induced Voltage and Current in Parallel Transmission Lines: Causes and Concern," IEEE Trans. on Power Delivery, Vol. 23, Oct. 2008.
[2] IEEE General Syst. Subcom., "Electromagnetic effects of overhead transmission lines practical problems, safeguards, and methods of calculation," IEEE Trans. Power App. Syst., PAS-93, May 1974.
[3] IEEE General Syst. Subcom., "Electrostatic effects of overhead transmission lines Part II-Methods of calculation," IEEE Trans. Power App. Syst., PAS-91, Mar. 1972.
[4] IEEE General Systems Subcom., "Electrostatic effects of overhead transmission lines Part I-Hazards and effects," IEEE Trans. Power App. Syst., PAS-91, Mar. 1972.
[5] IEEE PES Special Publication, "Modeling and Analysis of System Transients Using Digital Programs, IEEE PES Publication Catalog No. 99TP133-0.
[6] Electric Power Generation, Transmission and Distribution, OSHA 29 CFR 1910.269.

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