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Analysis of transient overvoltages caused by energization of multi-conductor transmission lines

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This paper presents a detailed study of the behavior of transient overvoltages in high-voltage transmission systems, using simulations in alternative transients program/electromagnetic transients program (ATP/EMTP) software. Two representative cases were analyzed: the first involves the sequential energization of an initially de-energized 230 kV circuit, while the second corresponds to the reclosing of a 400 kV circuit after opening due to a fault, in the presence of an already energized adjacent circuit. The transmission lines were modeled using the JMARTI model, suitable for representing frequency-dependent phenomena characteristic of switching transients. Non-simultaneous phase-to-phase closure conditions were considered, which allowed the most critical overvoltage scenarios to be identified. In the first case, overvoltages reached values greater than 2 per unit (pu), while in the second, during reclosure, overvoltages of up to 2.33 pu were observed, corresponding to more than 1300 kV. Additionally, induced voltages in adjacent circuits were evaluated through 30 simulations, varying the distance between tower centers from 50 m to 500 m. The results showed a clear decrease in induced overvoltages with increasing distance, although significant values of up to 0.25 pu were recorded even at 200 m. The results obtained were compared with the basic insulation levels (BIL) recommended by international standards such as IEC 60071-1 and IEEE Std C62, demonstrating the need to implement mitigation strategies. This study highlights the importance of considering both the switching sequence and the physical configuration of the system in the design of reliable and safe transmission networks.

Keywords: transient overvoltages, ATP/EMTP, high-voltage transmission lines, electromagnetic coupling, insulation coordination

1 Introduction

Transient overvoltage analysis on transmission lines is essential to ensuring the safe and reliable operation of power systems. These phenomena can be caused by switching maneuvers, lightning strikes, or internal faults, and are especially relevant in high-voltage systems where insulation margins are narrow and the effects of transients are magnified. Overvoltages not only affect the circuit in which they originate but can also be induced in parallel or nearby lines due to electromagnetic coupling.

In this context, multiple investigations have addressed the problem from different perspectives. In [1], mutual coupling compensation techniques between parallel lines are explored to improve the performance of distance protections. It is concluded that magnetic coupling can affect impedance measurements and cause malfunctions in protection schemes if not properly considered. This problem is especially critical when conventional protections are used on parallel lines without adequate shielding or with short distances between conductors.

On the other hand, the study presented in [2] focuses on the evaluation of internal overvoltages in transformer windings, resulting from external transients such as switching or atmospheric discharges. Using detailed alternative transients program/electromagnetic transients program (ATP/EMTP) models, it is demonstrated that transients can concentrate in certain sections of the winding, causing local dielectric stresses capable of exceeding the design limits. These findings are relevant for the design of transformers and their coordination with the protection system.

Another important aspect is the analysis of induced voltages in auxiliary components and adjacent lines. In [3], induced voltages in control cables within high-voltage substations are examined due to inductive and capacitive coupling with the main conductors. This type of interference can generate spurious signals that affect the operation of control and protection systems, especially in environments where cables share trays or channels with power conductors.

Likewise, studies such as those presented in [4, 5] focus on the effects of lightning on overhead trans-

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mission lines. These works demonstrate that, even in the absence of a direct strike, a nearby lightning channel can induce significant overvoltages on parallel lines or signal conductors.

Together, these works support the need for detailed analyses using simulation tools such as ATP/EMTP, which allow for accurate modeling of the effects of switching, surges, and physical system configurations. This article contributes to this body of knowledge by systematically evaluating the generation of surges from energizing and reclosing operations, as well as electromagnetic coupling as a function of circuit spacing. This information is key for the design of protection schemes, insulation planning, and defining minimum distances between parallel transmission lines.

2 Characteristics of electromagnetic transients

Electromagnetic transients in power systems are characterized by involving a wide spectrum of frequencies, including traveling wave phenomena and distributed parameter effects on transmission lines [6, 7].

Traditionally, their analysis has been based on simplified models that describe wave behavior using first-order differential equations, allowing a functional approximation of the system under various disturbances [8, 9]. The accurate estimation of electrical variables such as voltage and current depends both on the detailed mathematical representation of individual components and on comprehensive system modeling under fault or switching conditions. Based on this information, numerical methods, computational simulations, or physical models can be applied to analyze the system's transient states at its natural frequencies [10].

However, the increasing complexity of modern power grids, driven by the integration of switched-mode transformers, energy storage systems, and distributed renewable generation, demands a re-evaluation of conventional mitigation strategies and insulation coordination criteria [11, 12]. In particular, accurate modeling of transmission lines is essential to adequately reproduce high-frequency transient phenomena. This involves considering overhead lines as elements of indefinite length within the system, which requires a formulation that guarantees model fidelity during the occurrence of complex disturbances. In practice, this type of study presents recurring challenges related to the adequate representation of transmission lines [10]. Therefore, the model must meet specific accuracy criteria based on the analysis objectives. In this context, recent research has proposed significant improvements in the modeling of critical system components, contributing to a more robust characterization of transient phenomena [13].

2.1 Overvoltages caused by the closure of unloaded lines

The closure of empty transmission lines is a common operation in electrical systems. The surges generated during this process are due to the abrupt transition of electrical conditions, as the line voltage can change instantaneously upon connection to a source. These surges constitute one of the main sources of switching transients in power systems [14].

This phenomenon can be classified into two main situations:

- Planned shutdown, such as when commissioning new or repaired lines.
- Automatic reconnection after a temporary fault, where initial conditions may not be zero, generating more severe surges.

2.1.1 Power surges caused by planned shutdown

When the line is closed under normal conditions, there are no residual voltages or ground faults. In this scenario, the three phases are balanced, and the line is considered to be in a zero initial state. For the analysis, a single-phase line with no coupling between conductors is studied. A T-shaped model is used, which behaves like an LC oscillatory circuit, as shown in Fig. 1.

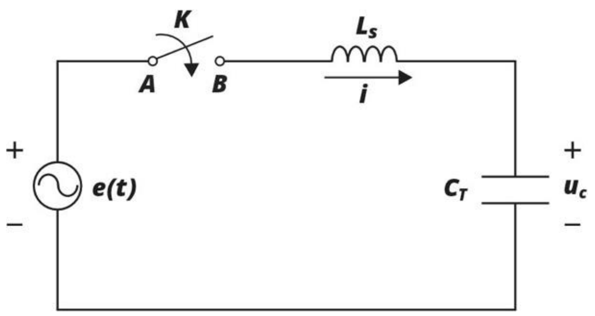

Fig. 1. Equivalent circuit for closing lines without load

The natural oscillation frequency is given by

$$f_0 = \frac{1}{2\pi\sqrt{L_S C_T}} \quad (1)$$

During the initial transient, the source can be considered to have constant amplitude E, depending on the switch closure angle. In the worst case, the differrential equation for the voltage across the capacitor u_c is derived as [6, 15]:

$$E_m = L_S \frac{di}{dt} + u_C \quad (2)$$

and considering that

$$i = C_T \frac{du_c}{dt}$$

we obtain

$$L_s C_t \frac{d^2 u_c}{dt^2} + u_c = E_m. \tag{3}$$

3 Case study

A detailed analysis of a 230 kV transmission line is presented below. The study focuses on the evaluation of transient overvoltages caused by circuit breaker closures, as well as the characterization of induced voltages in adjacent circuits due to electromagnetic coupling phenomena.

3.1 Induction in 230 kV *circuits*

Figure 2 shows the analyzed system, which corresponds to a 230 kV, double-circuit, three-phase transmission line commonly used in Mexico's electrical infrastructure. This line extends 90 km, connecting the El Caracol Hydroelectric Plant with the Mezcala electrical substation.

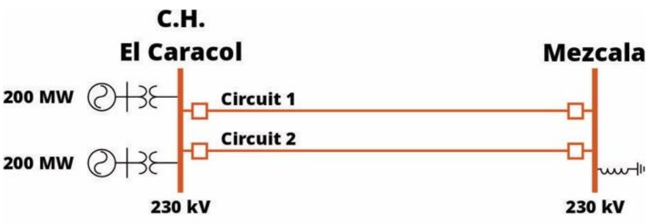

Fig. 2. 230 kV three-phase double circuit

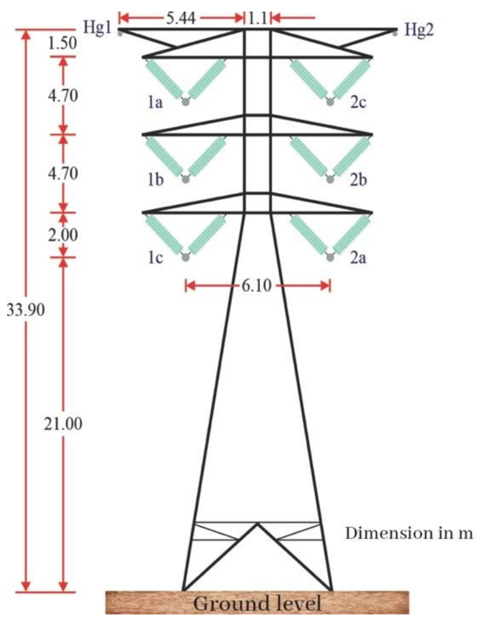

Fig. 3. Geometric configuration of the 230 kV line

The geometric arrangement of the phases and guard wires is shown in Fig. 3, while the key electrical parameters of the system are summarized in Tab. 1. An ideal transposition of the phases was assumed, as well as a direct grounding of the guard wires through the supporting metal structures, which significantly influences the electromagnetic coupling behavior.

Table 1. 230 kV transmission system data

Variable	Value
Nominal voltage	230 kV
Frequency	60 Hz
Number of circuits	2
Number of conductor per phase	1
Outer radius of the conductor	1.475 cm
Conductor resistance	0.0620 Ω/km DC
Number of guard wires	2
Outer radius of the guard wire	0.489 cm
Resistance of the guard wire	1.463 Ω/km DC
Soil resistivity	100 Ω · m

The analysis was carried out in ATP/EMTP, using the JMARTI model to represent the overhead line. This model allows for an accurate representation of frequency-dependent propagation effects, making it particularly suitable for the analysis of electromagnetic transients, such as those induced by switching operations.

The modeled scheme is presented in Fig. 4, which considers an initial situation in which both circuits are de-energized. The sequential closure of breaker CB1-1 is performed with a strategy designed to maximize overvoltages, applying phase closure times of 0, 0.005555, and 0.01111 s for phases A, B, and C, respectively, in synchrony with the source voltage peaks.

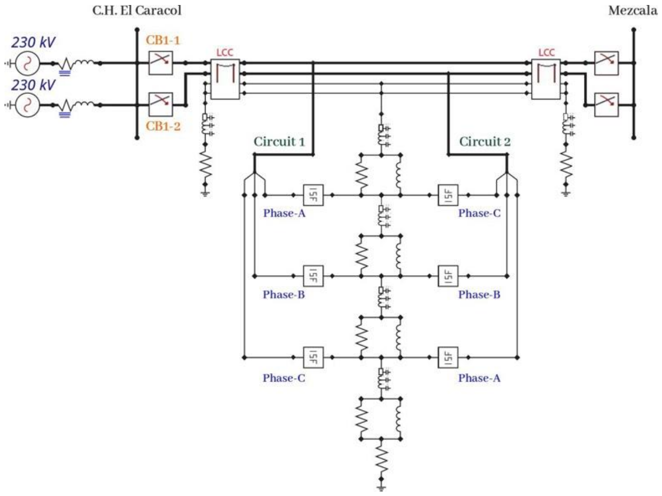

Fig. 4. Modeling of the 230 kV power grid

As shown in Fig. 5, the transient overvoltages recorded on circuit 1 exceeded 2 per unit (pu), reaching peaks above 650 kV. This represents more than twice the nominal peak voltage (325.26 kV), confirming the criticality of the energization phenomenon on long, unloaded lines. The amplitude of these overvoltages can compromise the dielectric integrity of the insulation equipment if appropriate mitigation strategies, such as controlled synchronization or precharge resistors, are not employed.

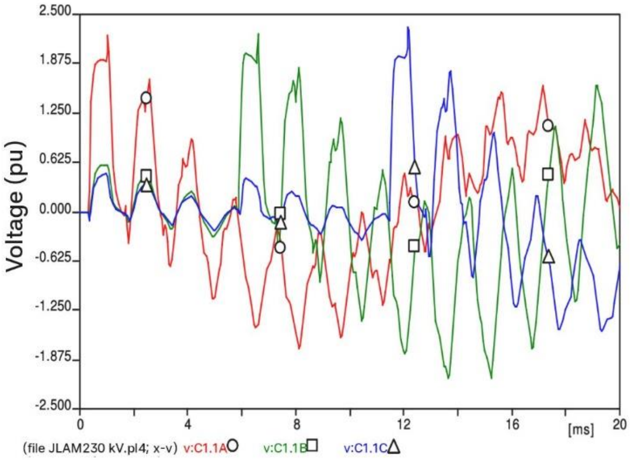

Fig. 5. Overvoltages presented in circuit 1 with sequential closing

Figure 6 shows the induced voltages in circuit 2, which remained de-energized during the shutdown. The maximum values recorded were 0.55 pu, 0.53 pu, and 0.41 pu for phases A, B, and C, respectively, with the maximum value equivalent to 178.9 kV. These induced overvoltages are the result of transient electromagnetic coupling between the two circuits, which share support structures.

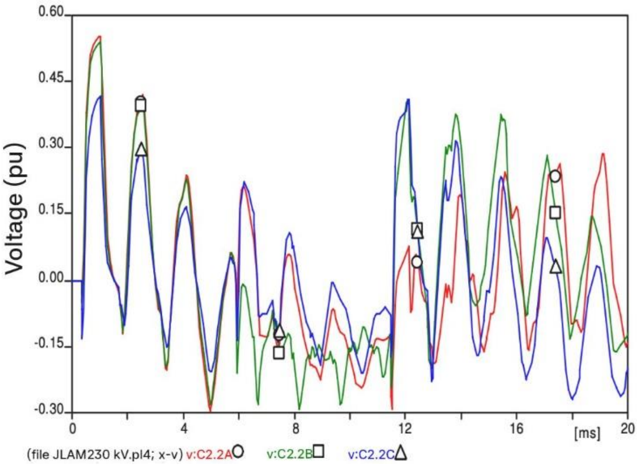

Fig. 6. Induced overvoltages in circuit 2 with sequential closing

It should be noted that, although circuit 2 is not energized, the induced overvoltages reach significant levels that could generate internal or external disruptive discharges in connected equipment.

4 Results and discussion

4.1 Induction in 400 kV *circuits*

This second case study analyzes the electromagnetic behavior of two 400 kV three-phase circuits. Figure 7 shows the system analyzed, representing a typical configuration in Mexico, consisting of two transmission lines connecting the Lázaro Cárdenas Potencia substation with the Pitirera substation, with a total length of 120 km.

Fig. 7. 400 kV three-phase double circuit

The geometric arrangement of the towers and phases is shown in Fig. 8, and the electrical parameters of the system are detailed in Tab. 2. An ideal phase transposition and the existence of two grounded guard wires directly through the support structures are considered.

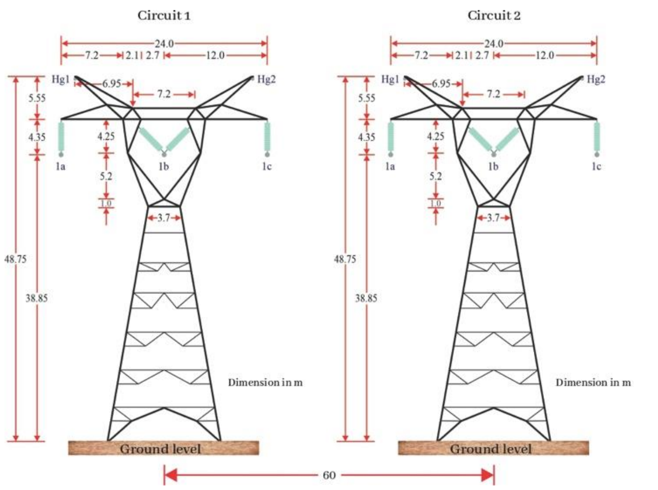

Fig. 8. Geometric configuration of the 400 kV line

During the ATP/EMTP simulation, both circuits are initially energized. In the event of a fault in circuit 1, breaker CB1-1 opens to isolate the fault, and then reclosing once the disturbance has cleared. The analysis focuses on both the overvoltages generated during reclosing in circuit 1 and the overvoltages induced in circuit 2, which remains operational throughout the event.

Table 2. 400 kV transmission system data

Variable	Value
Nominal voltage	400 kV
Frequency	60 Hz
Number of circuits	2
Number of conductor per phase	1
Outer radius of the conductor	1.599 cm
Conductor resistance	0.0513 Ω/km DC
Number of guard wires	2
Outer radius of the guard wire	0.489 cm
Resistance of the guard wire	1.463 Ω/km DC
Soil resistivity	100 Ω · m

As shown in Fig. 9, maximum overvoltages of 2.33 pu, 2.19 pu and 2.27 pu were recorded on phases A, B and C of circuit 1, corresponding to absolute voltages of 1318.04 kV, 1238.85 kV and 1286.82 kV, respectively (considering a base of 566 kV peak, corresponding to 400 kV RMS). These overvoltages represent severe, short-duration but high-magnitude transient phenomena that can compromise the dielectric strength of the system components.

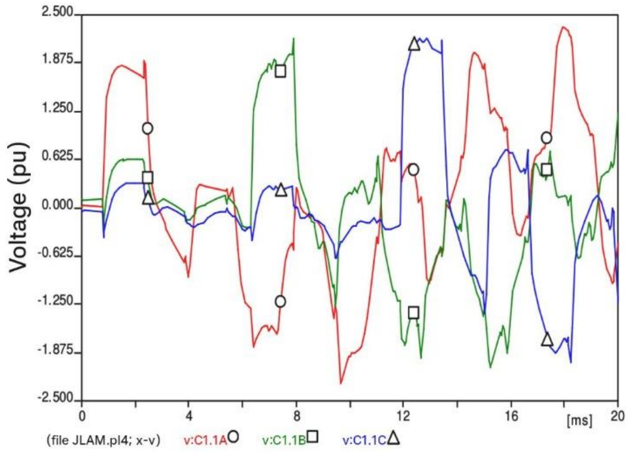

Fig. 9. Overvoltages presented in circuit 1

These magnitudes represent significant transient phenomena, which must be analyzed within the framework of insulation coordination. According to IEC 60071-1, the basic insulation levels (BIL) for 400 kV systems are typically around 950 kV for switching impulses [16, 17]. IEEE Std C62.82.1 establishes that transient overvoltages during switching operations must remain within safe margins to avoid disruptive discharges in the system equipment [18].

On the other hand, Fig. 10 shows the induced voltages in circuit 2, recording values of 1.38 pu, 1.43 pu and 1.51 pu in phases A, B and C, corresponding to 780.64 kV, 809.83 kV and 855.25 kV, respectively.

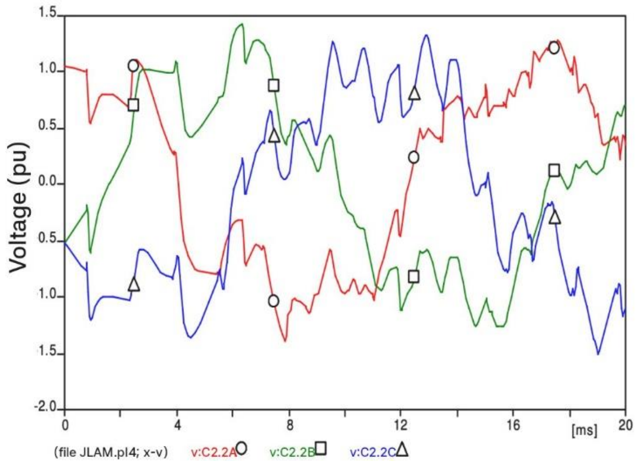

Fig. 10. Overvoltages presented in circuit 2

Although these overvoltages do not exceed the basic insulation levels typically established by standards such as IEC 60071-1 for 400 kV systems, they do represent significant values that could contribute to premature insulation wear, especially if they occur repeatedly or in combination with other transient phenomena. This result highlights the importance of evaluating electromagnetic interactions between adjacent circuits, even when both are operating, as well as strengthening insulation coordination and system design to prevent unwanted couplings.

4.2 Variation of the distance between 400 kV *circuits for induced voltage analysis*

To quantify the impact of physical separation between parallel lines on electromagnetic coupling levels, a series of 30 simulations were carried out at ATP/EMTP. The distance between tower centers was modeled from 50 m to 500 m, holding the geometric phase configuration and other electrical parameters constant. In each case, the maximum induced overvoltages in circuit 2 resulting from the energization of circuit 1 were measured.

Figure 11 shows the evolution of the induced voltage as a function of line spacing. A clear downward trend is observed: the maximum induced voltage value decreases as the distance between the circuits increases. However, even with a separation of 200 m, values of up to 0.25 pu are recorded, while for distances close to 400 m, the induced voltages remain on the order of 0.1 pu.

These results demonstrate the sensitivity of electromagnetic coupling between parallel transmission lines to their physical separation and underscore the importance of considering this phenomenon in the design of line corridors, especially in high-voltage systems where isolation margins are critical.

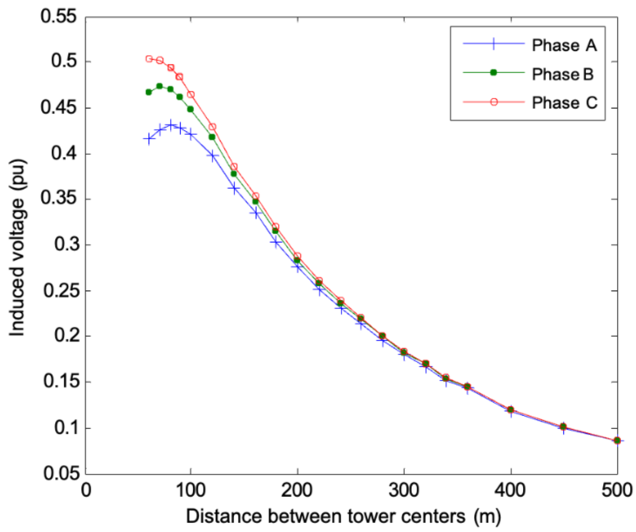

Fig. 11. Induced voltage

5 Mitigation strategies for future power grid designs

The results obtained allow us to propose a set of mitigation strategies aimed at reducing the impact of transient overvoltages, both on energized circuits and adjacent lines. These measures can be implemented during the design, planning, and operation stages of high-voltage networks, with the goal of increasing system reliability and extending equipment life.

5.1 Controlled switch closing timing

The simulations performed show that the closing time of each phase has a direct influence on the magnitude of the generated overvoltages. In this sense, the use of switches with phase-controlled synchronization (controlled switching) minimizes transient peaks during energizing or reclosing maneuvers by avoiding closures at the peaks of the voltage wave. This strategy significantly reduces dielectric stresses on the equipment without requiring modifications to the existing infrastructure.

5.2 Application of pre-closing resistors

The temporary addition of resistors in parallel with the breakers before final closing is an effective measure to dampen the initial oscillation and limit the amplitude of overvoltages, especially during vacuum closing of long lines. This technique improves insulation coordination and reduces the risk of electrical overstress on system components.

5.3 Optimization of separation between parallel lines

The parametric analysis performed confirms that increasing the physical distance between parallel circuits significantly reduces voltage levels induced by electromagnetic coupling. This finding supports the need to establish minimum separation criteria in the design of electrical corridors, particularly in contexts where future capacity expansions or coexistence of lines of different voltage levels are anticipated.

5.4 Reinforcement of the shielding and grounding system

The effective connection of grounding wires through metallic structures reduces inductive and capacitive coupling between adjacent circuits and facilitates transient dissipation. Ensuring low grounding impedance is essential to minimize induced overvoltages and guarantee adequate protection of control, signaling, and protection systems.

5.5 Insulation coordination based on detailed simulations

Since observed overvoltages can reach levels close to or even higher than the values recommended by international standards, it is essential that insulation coordination consider realistic operating scenarios. The use of tools such as ATP/EMTP allows for modeling specific operating conditions, which facilitates the definition of appropriate safety margins for the equipment involved.

Together, these strategies represent technically feasible actions aligned with international best practices. Their implementation contributes to strengthening the design of more robust, resilient, and safer electrical infrastructures in the face of high-magnitude transient events.

6 Conclusion

In this work, transient overvoltages generated during energizing and reclosing maneuvers in 230 kV and 400 kV transmission systems were analyzed using ATP/EMTP simulations. The results show that overvoltages can exceed critical values, reaching up to 2.33 pu in certain cases, implying peak voltage levels that approach or exceed the basic insulation limits established by international standards such as IEC 60071-1 and IEEE Std C62.

The importance of considering the phase closure time sequence to simulate realistic switching conditions was also demonstrated, as this significantly affects the magnitude of overvoltages. It was also observed that induced overvoltages in adjacent circuits, even when energized, can reach significant values that compromise the integrity of the insulation if appropriate measures are not taken.

The study of the influence of the distance between parallel lines showed a significant decrease in induced overvoltages as the separation between circuits increased, confirming the need to establish appropriate minimum distances in the design of electrical corridors to minimize risks.

Finally, the results underscore the importance of implementing mitigation strategies, such as controlled switch synchronization, the use of pre-closure resistors, and the installation of surge protection devices, to ensure the reliability and operational safety of the transmission system.

References

[1] O. Donovan, M. Barry, N. Connell, and E. Cowhey, “Mutual coupling compensation techniques used for distance protection of parallel lines,” *Energies.,* vol. 14, no. 7, pp. 1-15. Mar. 2021.

[2] J. Furgał, M. Kuniewski, and P. Pająk, “Analysis of internal overvoltages in transformer windings during transients in electrical networks,” *Energies.*, vol. 13, no. 10, pp. 1-20. May. 2020.

[3] A. Shafy, A. Emam, S. Ghania, and A. Hamza, “Analysis and mitigation techniques of switching overvoltages for A 500 kV transmission line,” *Int. Electr. Eng. J., IEEJ.*, vol. 7, no. 3, pp. 2196-2203. 2016.

[4] J. Furgał, “Influence of lightning current model on simulations of overvoltages in high voltage overhead transmission systems,” *Energies.*, vol. *13 no.* 2, pp. 1-10. Jan. 2020.

[5] S. Abouzeid, G. Shabib, and A. Mohamed, “Induced voltages on overhead transmission lines because of nearby included lightning channel,” *IET Generation, Transmission & Distribution.*, vol. 9, no. 13, pp. 1672-1680. Oct. 2015.

[6] J. Li, “Measurement and analysis of overvoltages in power systems,” *John Wiley & Sons*., pp. 1-26. 2018.

[7] J. A. Martinez-Velasco, “Power system transients: parameter determination,” *CRC press*. 2017.

[8] L. M. Castro et al., “Tower Models for Power Systems Transients: A Review,” *Energies*, vol. 15, no. 13, p. 4893, Jul. 2022.

[9] A. R. Oloko-Oba et al., “Transient Simulations and Analysis of Overvoltage Insulation Coordination of Extra High Voltage Transmission Lines,” *RJEES*, vol. 4, no. 2, pp. 66–76, Jun. 2024.

[10] D. Zychma, P. Sowa, “Electromagnetic transients in multi-voltage transmission lines during non-simultaneous faults,” *Energies*, *15*(3), 1046, 2022.

[11] Z. Hu et al., “Insulation Structure Design and Electric Field Simulation of 500 kV Isolation Transformer for HVDC Breakers,” *High Voltage*, vol. 7, no. 1, pp. 85–95, Feb. 2022.

[12] T. Ozawa et al., “Estimation of Transient Signals for the Insulation Coordination in a 10 kV Battery Energy Storage System,” in *IET Conf. Proc.*, Apr.

[13] A. S. Singh and K. S. Pandey, “Assessment of Insulation Coordination and Overvoltage for Utility Grids Integrated with Solar Farms,” *Energies*, vol. 17, no. 21, p. 5487, 2022.

[14] CIGRE Working Group C4.307, "Benchmarking of Control Strategies for HVDC Grids and AC Grids with a High Penetration of Renewables," CIGRE Brochure No. 602, 2014.

[15] Y. Liu, W. Xu, and S. Ran, "Calculation and Analysis of Switching Transients During Line Energization," *IEEE Transactions on Power Systems*, vol. 18, no. 2, pp. 580–585, May 2003.

[16] IEC 60071-1:2006+A1:2010, “Insulations co-ordination – part 1: definitions, principals and rules,” 2010.

[17] IEC 60071-2:2018, “Insulations co-ordination – part 2: application guidelines,” 2018.

[18] IEEE Standard C62.82.1™-2010, “IEEE standard for insulation coordination – definitions, principals, and rules,” 2010.

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