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Modeling and Evaluation of the Performance of Hybrid HV Lines Against Transient Lightning and Switching Surges

Ahmad Moradi [1], Mohsen Niasati [1,*]

[1] *Department of Electrical and Computer Engineering, Semnan University, Semnan, Iran*

**Corresponding author: Mniasati@Semnan.ac.ir*

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Abstract

Due to economic and technical constraints, hybrid lines (OH line - cables) remain necessary in suburban and urban areas. A critical challenge in studying these hybrid lines is their performance under transient lightning and switching surges. These transient overvoltages risk a significant threat to the insulation of power grid equipment, with cables being particularly vulnerable. This article analyzes the critical parameters influencing the magnitude of transient overvoltages in hybrid lines and explores various methods for mitigating these surges. Utilizing EMTP-RV software for modeling and simulation, the article meticulously investigates the maximum stresses imposed on cable insulation by overvoltages. Additionally, it presents solutions and recommendations for reducing transient overvoltages to acceptable levels.

Keywords (Times New Roman - 11- Bold):
Hybrid transmission lines; GIS; Transient lightning surges; Switching.

1. Introduction

The use of hybrid overhead–underground cable transmission lines in and around major urban areas is often inevitable due to technical and economic considerations [1]. Similarly, overhead lines connected to gas-insulated substations (GIS) exhibit transient characteristics that are, to some extent, comparable to those of hybrid transmission systems. One of the main challenges associated with these configurations is their insulation performance under lightning and switching overvoltages, which can impose severe dielectric stresses on power system equipment, particularly at overhead-to-cable transition points [2]. The significant mismatch between the surge impedances of overhead lines and underground cables, together with their different wave propagation velocities, leads to complex wave reflection and refraction phenomena at cable termination points. These effects can result in considerable transient overvoltages, particularly when relatively short cable sections are installed between overhead line segments [1, 2].

Previous studies have investigated several factors affecting lightning-induced overvoltages, including lightning current characteristics, striking location, tower footing resistance, insulation flashover, back-flashover, and surge arrester installation [3]. However, the effects of surge arrester grounding resistance, multiple arrester installations on adjacent towers, and switching operations in GIS substations, particularly during circuit breaker closing, require further investigation. High-voltage surge arresters are widely employed to mitigate transient overvoltages, with their selection and application addressed in IEC 60099-4.

Nevertheless, effective insulation coordination in hybrid transmission systems requires a comprehensive assessment of both lightning- and switching-induced transients. This paper investigates the transient performance of a 400-kV hybrid overhead–underground cable transmission line connected to a GIS substation. Using EMTP-RV simulations, the maximum transient overvoltages and associated cable insulation stresses are evaluated. The main contributions of this study are as follows:

1. Investigation of arrester grounding resistance: Evaluating the influence of the grounding resistance of surge arresters installed at cable termination points on their protective performance.
2. Assessment of multiple surge arrester installations: Analyzing the effectiveness of installing additional surge arresters on transmission towers adjacent to cable termination points in reducing transient overvoltages.

3. Analysis of GIS switching overvoltages: Investigating closing-induced overvoltages associated with GIS circuit breakers and evaluating the effectiveness of pre-insertion resistors (PIRs) in mitigating these transients.

2. Methodology

Two 400-kV network configurations are modeled in EMTP-RV to investigate the transient performance of hybrid overhead–underground cable transmission lines under lightning and switching conditions. The first configuration consists of an overhead line connected to an underground cable and an air-insulated substation (AIS), and is used to evaluate lightning-induced overvoltages. The second configuration represents a GIS substation connected to an overhead line through an underground cable, enabling the assessment of switching-induced transients. In both configurations, the analysis focuses on the terminal sections of the transmission lines and, particularly, on the overhead-to-cable transition points. Lightning transients are simulated using the CIGRE WG 33-01 current waveform model. A 100-kA negative lightning stroke directly striking phase A is considered as the reference case.

The overhead line comprises a 3.15-km single-circuit section equipped with ACSR Curlew conductors and two galvanized steel shield wires. The underground cable consists of 630-mm² XLPE-insulated single-core conductors, installed at a depth of 1 m, with a 0.5-m spacing between adjacent cables. Frequency-dependent Marti models are employed to represent the overhead lines and underground cables. The transient behavior of transmission towers is also considered to account for their high-frequency response and grounding characteristics. Furthermore, the GIS substation is represented using lumped equivalent elements, primarily capacitive components, to capture the high-frequency characteristics of very fast transient overvoltages (VFTO) generated during switching operations.

A comprehensive set of simulation scenarios is conducted to identify the key factors affecting transient overvoltages at cable termination points. For lightning events, the effects of tower footing resistance during shield-wire strikes, surge arrester installation, arrester grounding resistance, multiple arrester installations on adjacent towers, and underground cable length are investigated. For GIS switching events, the influence of circuit breaker closing operations and the application of pre-insertion resistors (PIRs) are evaluated. The resulting transient voltage waveforms are compared to assess the severity of insulation stresses at cable terminations and determine the effectiveness of different mitigation strategies.

3. Discussion and Results

This paper investigated the transient performance of a 400-kV hybrid overhead–underground cable transmission line under lightning and GIS switching conditions using high-frequency modeling and EMTP-RV simulations. The effects of key parameters on transient overvoltages at overhead-to-cable transition points and cable-to-GIS connections were evaluated, and various mitigation strategies were assessed in terms of their effectiveness in reducing insulation stresses. The results demonstrated that installing surge arresters at cable termination points plays an essential role in limiting transient overvoltages and reducing dielectric stresses on cable insulation and associated equipment.

However, their protective performance is strongly influenced by the grounding resistance. Reducing the arrester grounding resistance significantly improves its effectiveness in limiting overvoltages. Furthermore, in regions with high lightning activity or where tower footing resistance is relatively high, installing additional surge arresters on multiple towers near the substation can provide enhanced protection for hybrid transmission lines. The cable length was also identified as an important factor influencing transient wave propagation and overvoltage distribution along hybrid transmission systems.

Therefore, the necessity of installing surge arresters at both ends of underground cables should be carefully evaluated according to cable length and network characteristics. This is particularly important because the mismatch between the surge impedances and propagation velocities of overhead lines and underground cables can produce considerable insulation stresses at their transition points. Finally, the investigation of GIS switching operations revealed that the application of pre-insertion resistors (PIRs) is an effective approach to reducing both the magnitude and duration of switching-induced transient overvoltages. Overall, the findings highlight that reliable insulation protection in hybrid transmission systems requires a coordinated approach considering line and cable characteristics, grounding conditions, surge arrester configuration, and GIS switching equipment. The appropriate combination of these measures can significantly reduce dielectric stresses and improve the operational reliability of high-voltage hybrid transmission lines.

4. References

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