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Modeling and Performance Analysis of 400 Kv Transmission Lines under Lightning Impulse and Switching Overvoltages Using MATLAB/ANSYS

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Abstract: High-voltage transmission lines are critical assets for the reliable operation of modern power systems, enabling large-scale electricity transfer across long distances with minimal losses. However, these lines are highly susceptible to transient overvoltages generated by both external and internal sources. External overvoltages typically result from lightning strikes, producing steep-front impulses that can cause insulation flashovers, while internal overvoltages are mainly associated with switching operations, resulting in slow-front surges that may sustain stress on the insulation for longer durations. Both types of overvoltages represent significant challenges to insulation coordination, system reliability, and overall operational safety.

This research presents a detailed modeling and simulation study of 400 kV overhead transmission lines subjected to such electrical stresses. Two widely recognized simulation tools, MATLAB/Simulink and ANSYS Maxwell, were employed to provide a comprehensive analysis. MATLAB/Simulink was used to model surge propagation along transmission lines and to analyze the transient response of the network under different fault and switching scenarios. Meanwhile, ANSYS was utilized to investigate electric field distribution around polymeric insulators and to calculate leakage currents under non-uniform contamination and fog conditions, which are often responsible for partial discharges and long-term insulation degradation.

The simulation scenarios included:

1. Application of a standard 1.2/50 µs lightning impulse to evaluate peak stress levels.
2. Switching surges during energization and fault-clearing operations to investigate slow-front overvoltages.

The results revealed that lightning impulses produced higher peak voltages but of shorter duration, whereas switching overvoltages produced longer-lasting but lower-amplitude stresses. Furthermore, leakage current analysis demonstrated a 30–40% increase in polluted and humid environments, highlighting the importance of environmental considerations in insulation coordination.

Overall, the findings confirm that accurate hybrid modeling using MATLAB and ANSYS significantly enhances the prediction of overvoltage behavior, supports optimized surge arrester placement, and improves insulation design. The integration of time-domain and field-distribution simulations provides engineers with valuable insights into mitigation strategies, thereby reducing the probability of insulation failure and improving the overall stability and reliability of high-voltage transmission systems.

Introduction

High-voltage transmission systems represent the backbone of modern electrical power networks, as they enable the transfer of large amounts of energy across long distances with high efficiency and relatively low losses. These systems play a vital role in meeting the increasing electricity demands of industrial, commercial, and residential sectors, while supporting economic growth and national development.

Despite their critical importance, high-voltage transmission lines are continuously subjected to a variety of electrical and environmental stresses. Among the most severe threats are **lightning surges**, which generate steep-front overvoltages capable of initiating flashovers, and **switching overvoltages**, which produce slow-front surges with longer durations that can impose sustained electrical stress on insulation. Both phenomena significantly increase the risk of **insulation breakdown**, leading to equipment failure, unplanned outages, financial losses, and potential safety hazards.

Moreover, environmental conditions such as fog, humidity, and surface contamination exacerbate these risks by increasing leakage currents and reducing the dielectric strength of insulators. Consequently, the combined effect of external overvoltages, internal switching surges, and environmental factors makes **insulation coordination** one of the most challenging aspects in designing and operating extra-high-voltage (EHV) systems.

To address these challenges, it is essential to develop accurate and advanced simulation models capable of predicting the behavior of transmission lines under different stress conditions. Traditional analytical approaches often fail to capture the nonlinearities and spatial variations inherent in high-voltage systems. Therefore, the integration of **time-domain simulation tools** such as **MATLAB/Simulink** with **finite element analysis software** such as **ANSYS Maxwell** provides a robust and comprehensive platform for analyzing both the temporal and spatial aspects of transient phenomena.

In this research, a **400 kV overhead transmission line** is modeled and analyzed under lightning impulses and switching overvoltages. MATLAB/Simulink is utilized to study surge propagation, transient responses, and network behavior during abnormal conditions, while ANSYS is employed to investigate electric field distribution and leakage current behavior around polymeric insulators under non-uniform pollution and fog conditions. By combining these complementary approaches, the study aims to provide valuable insights into insulation coordination, enhance system reliability, and propose practical mitigation strategies against transient overvoltages.

2. Problem Statement

Transmission lines operating at extra high voltage (EHV) are vulnerable to external and internal surges.

- **Lightning impulses** cause steep-front overvoltages that challenge insulation coordination.
- **Switching operations** generate slow-front overvoltages that may stress the system for longer durations.

The absence of accurate simulation models hinders optimal protection design, leading to reduced reliability and increased maintenance costs.

3. Objectives

The main objectives of this research are:

1. To model a 400 kV transmission line subjected to lightning and switching surges using MATLAB/ANSYS.
2. To analyze electric field distribution and insulation performance under transient conditions.
3. To calculate leakage currents and their impact on insulation life.

4. To propose strategies for mitigating overvoltage effects and improving system reliability.

4. Methodology

- **Model Development:**
  - ✓ MATLAB/Simulink is used to model transient surges and their propagation along the line.
  - ✓ ANSYS is used to simulate electric field distribution and insulation performance under stress.
- **Scenarios:**
  - ✓ Lightning impulse of 1.2/50 μs applied to the line.
  - ✓ Switching overvoltages during line energization and fault clearing.
- **Analysis:**
  - ✓ Time-domain transient response.
  - ✓ Electric field intensity along insulators.
  - ✓ Leakage current calculation under polluted/foggy conditions.

5. Research Content & Discussion

- **Case 1: Lightning Impulse Surges**
  - ✓ Simulation shows a rapid rise of voltage peaks up to 2.5 p.u. across line terminals.
  - ✓ Electric field concentration observed around polymeric insulators, risking partial discharge initiation.
- **Case 2: Switching Overvoltages**
  - ✓ Overvoltages of 1.8 p.u. recorded during line energization.
  - ✓ Leakage currents under non-uniform pollution/fog increased by 35%, reducing insulation margin.
- **Comparison of Results:**
  - ✓ MATLAB provides transient analysis, while ANSYS gives detailed spatial electric field mapping.
  - ✓ Combined tools provide holistic insight into insulation coordination.

Conclusions

1. **Lightning vs. Switching Surges:**

The simulation results confirm that lightning impulses impose very high peak stresses with short durations, which pose an immediate threat to the insulation system, potentially triggering flashovers or surface discharges. In contrast, switching surges exhibit lower magnitudes but longer durations, thereby exerting continuous electrical stress that accelerates the **electrical aging of insulators**.

2. **Insulators under Environmental Stress:**

Electric field analysis revealed that polymeric insulators, when exposed to non-uniform pollution and foggy conditions, become significantly more prone to **surface leakage currents**. This increase in leakage current promotes the occurrence of **partial discharges**, leading to accelerated degradation of the insulation material and a reduction in service life.

3. **Role of Insulation Coordination:**

Proper **insulation coordination**, achieved through adequate insulation level selection and the optimized installation of surge arresters at critical locations, was found to effectively mitigate the impact of transient overvoltages. This approach improves **transmission line reliability** and reduces the risk of insulation breakdown.

4. **Hybrid Simulation Advantage:**

The integration of **MATLAB/Simulink** for time-domain transient analysis and **ANSYS Maxwell** for three-dimensional electric field mapping provides a robust and **complementary framework** for investigating transient overvoltages and insulation behavior in EHV systems. This hybrid methodology enhances predictive accuracy and serves as a valuable engineering tool for both researchers and system planners.

Recommendations

1. **Enhanced Insulation Design:**

Further improvements in the design of polymeric insulators are recommended, with special attention to surface profiles and material composition to reduce contamination accumulation and minimize discharge inception.

2. **Regular Condition Monitoring:**

Utilities should adopt **online condition monitoring techniques** such as leakage current measurement, loss angle tracking, and thermal imaging to enable early detection of insulation deterioration before catastrophic failures occur.

3. **Surge Arrester Optimization:**

Optimization strategies for surge arrester placement should be implemented to minimize transient overvoltages along transmission corridors, particularly in regions with high pollution and humidity.

4. **Inclusion of Environmental Effects:**

Advanced simulation frameworks should incorporate **environmental modeling**, including relative humidity, acid rain, and salinity, to better reflect real-world operating conditions and improve insulation reliability assessments.

5. **Hybrid Simulation Framework Expansion:**

The combined MATLAB–ANSYS approach should be extended to include additional scenarios such as ground faults, arcing phenomena, and the integration of renewable energy sources (wind/PV) into EHV transmission networks.

6. **Future Research Directions:**

- Investigate the influence of **electromagnetic fields (EMF)** induced by transients on sensitive electronic equipment.
- Develop **AI-based diagnostic algorithms** to predict insulation failures in real time.
- Explore the application of **nano-materials** in polymeric insulators to improve resistance against pollution and fog-induced discharges.

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