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A System-Level Review Of Lightning-Induced Overvoltages In Substations Considering Shielding Failure, Backflashover, And LEMP Effects

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Abstract: The lightning-induced overvoltage phenomenon poses a significant threat to insulation stress and failures in high voltage substations. Although much work has been done to understand the mechanisms of shielding failures (SF) and back flashover (BFO), the cumulative effect of both on overvoltage in substations, especially in the presence of lightning electromagnetic pulse (LEMP), has not been adequately explored in the past. This paper attempts to provide a comprehensive review on the subject by critically examining the phenomenon of lightning induced overvoltage in the context of lightning sources, transmission line behavior, and substation transients. A comparative evaluation of widely used lightning current models and attachment models (Electro geometric Model and Leader Progression Model) is conducted, highlighting their impact on predicted overvoltage levels. The analysis shows that conventional electromagnetic transient (EMT) approaches may significantly underestimate overvoltage due to neglect of LEMP effects, especially in BFO scenarios. Furthermore, the roles of multi-stroke lightning, grounding nonlinearity, and travelling wave interactions are critically examined. The review identifies key limitations in existing modeling approaches, including single-stroke assumptions and lack of integrated system-level analysis. Based on these findings, future research directions are proposed toward high-fidelity, multi-physics modeling frameworks for improved insulation coordination and lightning performance assessment in modern power systems.

Keywords-Lightning overvoltage shielding failure CIGRE Current model Heidler Current model back flashover substations insulation coordination Electro-geometric model Leader Progression Model LEMP**.**

I. INTRODUCTION

Lightning is one of the most important and critical natural phenomena that affects high voltage power system reliability and performance. This is in spite of the fact that tremendous advancements in insulation coordination, grounding, and surge protection devices [1,2]. Overvoltage due to lightning are one of the main reasons for insulation failure, equipment damage, and outages in a high voltage power system. This is a major issue in modern times, especially after the advent of EHV and UHV power systems, where the insulation level is compromised in substation design [3–5]. Substation is one of the important nodes in a power system, where high-value equipment such as transformers, circuit breakers, and instrument transformers are installed. Therefore, it is necessary to determine lightning-induced overvoltage so that reliable insulation coordination is achieved in accordance with international standards [6–8]. Overvoltage from transmission lines generally appear in substations in the form of travelling waves, where overvoltage interact in a complex manner due to impedance discontinuities, resulting in voltage amplification [9, 10]. There are two major processes through which lightning affects the transmission system. These two processes are shielding failure (SF) and back flashover (BFO). Shielding failure is a process through which lightning strikes the overhead wire by skipping the ground wire. In this process, high-value currents are injected into the system [11]. On the other hand, back flashover is a process through which lightning strikes a wire that is shielded. The striking effect of this process causes a sudden voltage that causes a failure in the entire insulator string. Although shielding failure and back flashover are different in nature, these two processes are responsible for causing transient over voltages in the system. Generally, shielding failure and back flashover have been studied independently using an electromagnetic transient (EMT) simulation technique in conventional research works [12,13]. However, recent research has shown that lightning electromagnetic pulse (LEMP) has an effect on transient overvoltage. In addition, conventional research has considered a single stroke of a lightning strike; however, a lightning strike is not a single stroke [14–16].

Although a large number of publications exist on the lightning performance of transmission lines and insulation coordination in substations, a comprehensive review that considers the overall behavior of lightning sources, transmission lines, LEMP Effect and substations simultaneously has not been found in the existing literature. Specifically, the combined effect of SF, LEMP, and multi-stroke lightning has not been addressed in the existing literature [17–22]. In the present paper, a comprehensive review of the overall behavior of lightning-induced overvoltages in substations has been presented by critically discussing the existing literature in the field. Specifically, the capabilities and limitations of different modeling approaches have been identified, and the overall behavior of the most important factors affecting the severity of lightning-induced overvoltages has also been addressed in the present paper.

2. Key Contributions and Novel Insights

The present research offers a comprehensive and critical evaluation of lightning-induced overvoltages in substations, particularly considering their combined influence of shielding failures, back flashover, and the lightning electromagnetic pulse. Unlike most conventional review articles, this paper takes a systems approach to integrate all stages of lightning performance.

Figure 1: is illustrated overall interaction between lightning phenomena, transmission systems, and substation

- **Unified System-Level Framework**: A framework is formulated that integrates lightning sources, attachment characteristics, transmission line behavior, and substation transient response. This framework facilitates a comprehensive understanding of overvoltage generation and propagation.
- **Integrated Analysis of SF, BFO, and LEMP** : An integrated analysis of shielding failures, back flashovers, and electromagnetic coupling is conducted in this paper. This analysis reveals that the combined effect of these phenomena is critical in determining overvoltage magnitude at substations, especially under tower lightning strikes.
- **Comparative Evaluation of Modeling Approaches**: A detailed comparison of lightning current models (CIGRE vs. Heidler) and attachment models (EGM vs. LPM) is presented, quantifying their impact on overvoltage prediction and insulation coordination.
- **Incorporation of Multi-Stroke Lightning Effects**: The limitations of single-stroke assumptions are critically examined, and the importance of multi-stroke lightning in increasing waveform steepness, cumulative effects, and voltage amplification is emphasized.
- **Travelling Wave Interaction Analysis:** A travelling wave-based interpretation is introduced to explain voltage amplification mechanisms at the transmission line–substation interface, including reflections, refractions, and impedance mismatch effects.

3. Fundamentals of Lightning Interaction with Transmission Systems

3.1 Lightning Parameters and their impact on the substation overvoltage

The parameters that are usually related to lightning currents are considered to have a vital impact on the level of intensity and characteristics of overvoltage that are generated in transmission systems, and this is considered to have a significant impact on the level of reliability and stability of electrical systems. In relation to this, lightning currents in the context of electromagnetic transient simulations are usually represented with analytical models, and in this context, it is noted that Heidler current models and CIGRE concave waveform models are predominantly used. Both the CIGRE concave and Heidler current model are considered to be powerful analytical models in relation to representing the complex nature of lightning currents, and while both models are considered to have effectively represented the essence of lightning currents, it is important to note that both models have considerable differences in relation to their leading edge characteristics and the transient response that is generated in electrical systems [23–25].

3.2. Lightning Current Models

3.2.1. Heidler Current Model

The Heidler lightning surge model used in this study features the direct lightning impulse model, which is one of its main categories. The Heidler model is among the most frequently used models for accurately analyzing transient overvoltages caused by lightning, owing to its realistic current profile, its endorsement as a reference model by standards organizations such as the International Electrotechnical Commission (IEC 62305-1), and its wide range of application areas While the calculations involved in this model are more complex than those in other models and require more computations, this complexity can be viewed as a disadvantage. However, it ultimately yields more realistic results compared to simpler models [26]. Heidler model is provided below

$$i(t) = \frac{I_0}{\eta} \cdot \frac{(t/\tau_1)^n}{1 + (t/\tau_1)^n} \cdot e^{-t/\tau_2} \tag{1}$$

where I_0 is the peak current, τ_1 is the front time constant, τ_2 is the tail time constant, n is the steepness factor, and η is a correction factor.

3.2.2. CIGRE Current Model

The CIGRE lightning current model is commonly used to represent how lightning current actually behaves. In this model, the current rises in a slightly curved (concave) shape and then gradually decreases over time [27]. This shape is quite similar to what is seen in real lightning waveforms. Because of this, the CIGRE model is considered reliable for practical studies. It is often used in insulation coordination and in simulations of electromagnetic transients, where a realistic representation of lightning current is important [28, 29].

CIGRE models are represented as

$$I(t) = At + Bt^n \tag{2}$$

where A and B are constants, t is time, and n is a waveform shaping exponent.

Table 1: Lightning Model Comparison

Model	Accuracy	Flexibility	Advantages	Limitations
CIGRE Model	Moderate	Low	Simple implementation	Limited representation of real lightning variability
Heidler Model	High	High	Realistic waveshape	Requires parameter tuning

Case Study: Lightning Overvoltage Analysis of 220 kV System

The system considered in this study comprises a 220 kV overhead transmission line feeding an air-insulated substation. The substation is equipped with a 160 MVA transformer rated at 220/110 kV. For the line representation, a phase conductor with a cross-sectional area of 525 mm² and a shield wire of 70 mm² are used. The insulator string is taken as 1270 mm in length, with a protection angle of 22°, reflecting typical shielding practice. A lightning strike is assumed to occur 900 m from the substation, allowing the resulting travelling waves and their effect on substation overvoltage to be examined.

The Fig. 2 waveform clearly shows a steeper front and higher peak magnitude for the CIGRE model compared to the Heidler model. The results show that considerable variation in overvoltage levels is predicted depending on the chosen model. For the CIGRE current model, a peak overvoltage of 500 kV is predicted, whereas for the Heidler first stroke and subsequent stroke models, overvoltages of 90 kV and 300 kV, respectively, are predicted. It is evident that overvoltages predicted by the CIGRE model are three times higher than those overvoltage that are simulated by using Heidler's model for successive strokes, whereas they are 12 times higher when Heidler's model for first stroke is used. From the above results, it is evident that a single-stroke representation may lead to inconsistent conclusions. Overvoltage predicted by the Heidler model for subsequent strokes are 233% higher than those predicted by the first stroke. The highest and most oscillatory overvoltages are given by the CIGRE model, thus it is a very conservative method. The Heidler models, on the contrary, have lower and less oscillatory overvoltages, with the subsequent stroke having the lowest overvoltages. This shows that the model used is very important in determining the level of overvoltages. There is no model that is universally best. The CIGRE model, which was developed by CIGRE, is best for conservative design, while the Heidler model is best for realistic transient analysis. [28, 30].

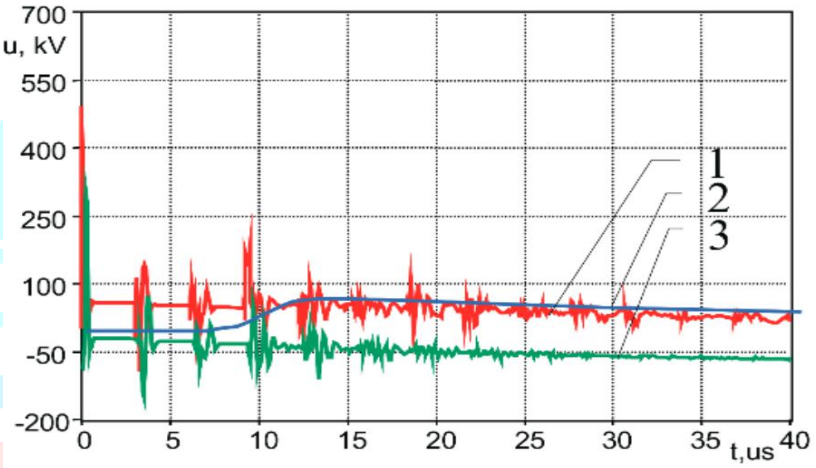

Figure 2: Comparison of substation overvoltage using different lightning current models (1) CIGRE model,(2) Heidler First stroke,(3) Heidler subsequent stroke

4. Lightning Overvoltage Mechanisms in Substations

4.1. Shielding Failure

The wires are installed above the phase wires in order to intercept the lightning strikes effectively. However, it is also very important to note that there is a possibility of shielding failure by the phase conductor due to the lightning strike [31]. This could further lead to flashover of the insulators, thereby de-energizing the transmission line. It is of major importance in the accurate evaluation of the maximum shielding failure current (MSFC) and lightning attachment for the correct evaluation of the lightning performance of the transmission line [32,33]. For the evaluation of this phenomenon, various models have been developed. Out of the various models developed for the evaluation of the performance of the transmission line in terms of shielding performance and shielding failure flashover rate, the Electrogeometric Model (EGM) and Leader Progression Model (LPM) are widely used. It has been observed that the rate of shielding failure in the case of transmission lines is much higher in the case of subsequent strokes rather than the first stroke currents. It has also been observed that the rate of shielding failure in the case of transmission lines is much more significant in the case of subsequent strokes rather than the first stroke currents [34]

4.1.1. Electrogeometric Model (EGM)

The Electrogeometric Model (EGM) is often used for estimating lightning attachment to transmission lines using striking distances. In general, taller and more exposed structures are more likely to be struck by a lightning discharge. In this context, the striking distances are related to the magnitude of the lightning current [35, 36]

$$r = AI^B \tag{3}$$

where r is the striking distance, I is the lightning current, and A and B are empirical constants.
Though the lightning attachment model is based on some assumptions, it is not the actual representation of the physical phenomena associated with the occurrence of being struck by lightning. There are better ways of modeling the lightning attachment by including more variables. Hence, the choice of the lightning attachment model plays a great role in the evaluation of the shielding failure and the resultant overvoltage in the substations, especially high-voltage substations. [38]

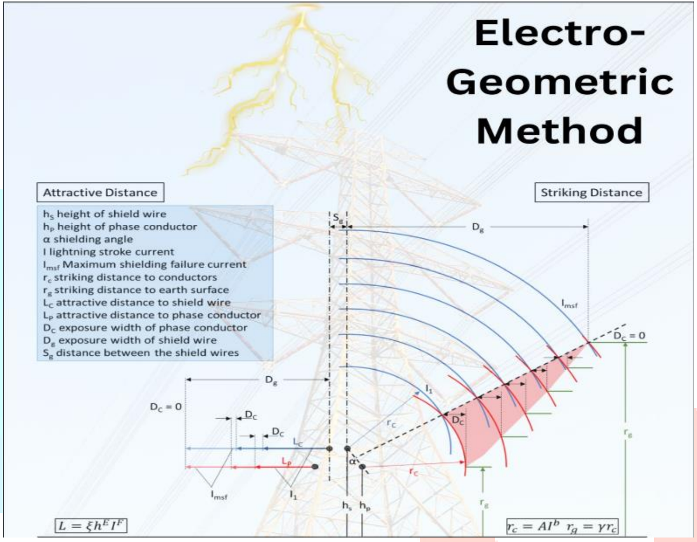

Figure 3: Electrogeometric model [37]

Advantages: Electrogeometric Model (EGM) is advantageous in that it is geometrically simple and computationally inexpensive. It is easy to apply in estimating attachment points for a lightning strike. It is a simple approach that is based on a striking distance concept and is very efficient in assessing shielding performance. It is most suitable for preliminary design and standard transmission line analysis.
Limitation: Although EGM is a simple approach, it is not very accurate since it fails to take into consideration the physical process of leader propagation and electric field changes. It is not a very effective approach in assessing transmission lines since it is not able to accurately predict the performance of EHV/UHV systems [3, 39].
Application: Application: EGM is most commonly used in transmission line design and is often used to evaluate shielding failures and protection zones. It is most commonly used for preliminary assessments since it is very efficient and easy to apply.

4.1.2. Leader Progression Model (LPM)

The downward lightning leader is represented by a charged line segment in the Leader Progression Model (LPM), and the electric field around objects is calculated using the Charge Simulation Method (CSM). As the downward leader approaches, it induces voltages and electric fields on the objects. Once a certain level of voltage and electric field is applied to the objects, the upward leader is initiated at the surface of the object. Then, the upward leader approaches the downward leader; at a certain point, the jump is made. [40–42] The model assumes a uniform charge distribution along the leader, with the charge density related to the return stroke current as:

$$q = 3.3 \times 10^{-6}\sqrt{I^2 + 500I} \tag{4}$$

To figure out when the upward leader starts we look at a things. One is the gap conditions. This is when the voltage across a gap is too high. The upward leader begins when this voltage is higher than a critical breakdown voltage. We also look at the electric field conditions. The upward leader starts when the average electric field is stronger than the voltage, in air. For a conductor that’s horizontal we can estimate the voltage needed for the leader to keep going.

$$U_c = \frac{2247}{1 + \left(\frac{5.15-5.49\ln(a)}{h\ln(2h/a)}\right)} \tag{5}$$

Additionally, corona inception and leader formation depend on the critical surface electric field given by:

$$E_c = 3000\,\delta\,m\left(1+\frac{0.03}{\sqrt{\delta r}}\right) \tag{6}$$

As the downward and upward leaders approach each other, the electric field in the gap increases until breakdown occurs. This typically happens at an average field strength of about 300 kV/m for positive lightning and 500 kV/m for negative lightning, leading to the final connection of the lightning channel.
Advantages: The Leader Progression Model is really good at predicting what will happen because it looks at how lightning moves upwards and downwards. This means we can get a realistic idea of how lightning will strike something. The Leader Progression Model is very useful for looking closely at how lightning behaves in complicated systems, like The Leader Progression Model.

Limitation: LPM is computationally heavy and requires multiple parameters and assumptions, which increases modeling complexity and limits its practicality for large-scale or routine engineering studies
Application: LPM is primarily used in advanced research studies, EHV/UHV system analysis, and detailed evaluation of lightning attachment and shielding performance where high accuracy is required.

4.1.3 Quantitative Comparison of Lightning Attachment Models

The Electro geometric Model or Electro geometric Model is not very good at showing how often shielding fails because it simplifies things much. The Electro geometric Model usually predicts a range of critical lightning currents but the Leader Progression Model or Leader Progression Model can handle many more scenarios for how lightning attaches to things. Studies have shown that the Leader Progression Model can predict when shielding will fail for a wider range of currents 20 to 50% more especially in Extra High Voltage and Ultra High Voltage systems.

When it comes to knowing where lightning will strike the Electro geometric Model assumes that lightning will always hit the same spots, which is not very accurate. The Leader Progression Model on the hand takes into account how the electric field changes and how lightning starts, which makes it much better at predicting where lightning will hit. The difference between the two models can be much as 30 to 40% especially in areas with complicated terrain.

The Electro geometric Model is fast to use because it uses math but the Leader Progression Model takes longer because it has to calculate the electric field and simulate charges many times. Even though the Leader Progression Model is more complicated it is more accurate with errors of 10 to 15% compared to 25 to 40% for the Electro geometric Model.
Neither the Electro geometric Model nor the Leader Progression Model fully understands the complex physics of how lightning interacts with power transmission systems. Both models do not do a job of predicting where lightning will attach and do not consider how the system responds to lightning. So it is very important to use these models with transient simulations to get accurate assessments of overvoltage at substations, like the Electro geometric Model and Leader Progression Model to really understand what is going on.

4.2 Back Flashover:

When lightning strikes a transmission tower or a shield wire a lot of flows through the transmission tower to the ground. This current makes a high voltage because of the way the transmission tower is designed. At the time the voltage on the power lines is not as high because of the way the transmission tower and the power lines and the shield wires interact with each other. The transmission tower and the shield wires and the power lines are all connected in a way that affects the voltage, on the power lines when lightning strikes the transmission tower or the shield wire.[64]

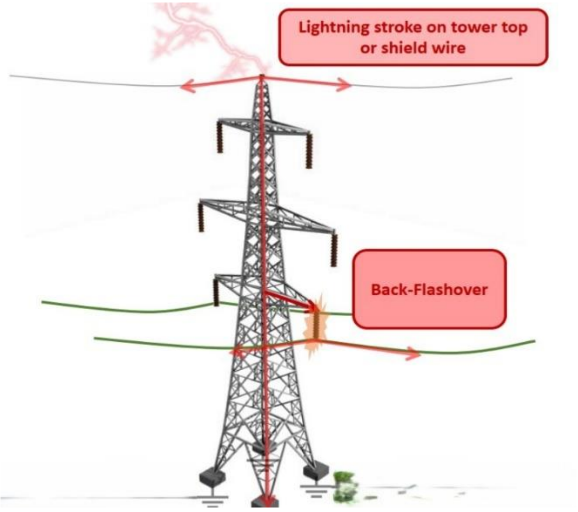

Figure 4: Back Fashover mechanism caused by lightning strike to transmission tower leading to insulation breakdown.

The voltage on the line insulator is the difference between the tower voltage and the induced conductor voltage. If the voltage on the line insulator is greater than the flashover voltage then an arc is established between the tower and the conductor. This arc lets the lightning move to the phase conductor, which results in a fault between the phase conductor and the shield wire known as back flashover of the line insulator [47]. Back flashover of the line insulator usually happens when there are high magnitude lightning currents and steep wave fronts. These steep wave fronts increase the voltage stress, across the line insulation of the line insulator [48].The analysis indicates that back flashover (BFO) occurs mainly as a result of transients rather than how strong the stroke was (with regard to the magnitude of the peak current). The ordering of strokes has a great effect on the overvoltage; using multiple strokes produces higher overvoltage even though the peak currents are smaller due to the reduced rise time and greater di/dt as compared to the first stroke. Specifically, we see that, in substation adjacent line segments, the voltage peak of the first stroke is 1.04 MV and will increase to 1.10 MV for subsequent strokes.
This variation is likely a result of the fast front characteristics of the voltage waveform as we have also seen increases of 6-22% in the overvoltage in 110 kV systems where the peak current is reduced to approximately 55-62% of the original value (the peak currents). We also see that spatial variation exists; Specifically the voltage peaks will reach approximately 2.27 MV when measured near substations compared to approximately 1.95 MV for remote locations; however, the mid-span location may reach as high as 5.9 MV due to higher inductive coupling and reflections. Lastly, discontinuity due to cable/overhead junctions produces large variations in voltage at the point of junction, which affects the occurrence of overvoltage. Notable increases in subsequent strokes continue to indicate incomplete Mitigation . The time response of voltage peaks several microseconds after a stroke and decayed over the next several milliseconds shows that BFO is not associated with steady-state conditions as it is driven by very fast transient phenomena.

Grounding resistance has a very large effect on tower potential rise and insulation stress, but using a defined (constant) resistance assumption limits the ability to properly represent real-world scenarios. In summary, the data indicate that MLS results in both cumulative and high-frequency effects, substantially increasing BFO susceptibility due to the inadequacy of traditional single-stroke, peak current-based conclusions; consequently, models must incorporate waveform steepness, multiplicity of strokes, spatial variability and transient dynamics in assessing insulation coordination reliability [22,49]The following software is used to analyze the transient in the power system. EMTP-RV / ATP-EMTP, PSCAD, MATLAB / Simulink (Simscape Power Systems), NETOMAC.

Aspect	SF	BFO	Comparative Insight
Governing Domain [50]	Controlled by lightning attachment characteristics	Controlled by tower ground transient response	Represents geometrical vs electromagnetic dominance
Sensitivity Nature [51, 52]	Dependent on exposure and shielding configuration	Dependent on grounding and insulation behavior	Indicates fundamentally different design dependencies
Response to Lightning Current	Probability-driven phenomenon	Severity-driven phenomenon	SF aspects occurrence, BFO governs overvoltage magnitude
Influence of Multi-Stroke	Modulates failure probability	Enhances cumulative voltage stress	BFO is more sensitive to waveform superposition effects
Role of Electromagnetic Coupling	Limited influence	Strong interaction with induced eects	Coupling effects are critical mainly in BFO scenarios
Modeling Perspective	Attachment-focused evaluation	Transient response-focused evaluation	Requires integration for realistic system representation
Arrester Energy Absorption [53, 54]	low to moderate energy stress due to indirect exposure and partial shielding	High energy absorption due to direct grounding surge and tower potential rise	Arresters play a more critical protective role in BFO, where energy dissipation requirements are significantly higher

This is like how the soil behaves the shape of the tower and getting hit by lightning times all these things can make the situation more complicated and harder to predict. We use things like shield wires and surge arresters to protect the system. Even these cannot completely stop back flashover from happening. So to really understand what is going on we need to look at all the things that can affect the system, not one or two things at a time

5. Lightning Electromagnetic Pulse (LEMP)

Lightning electromagnetic pulse (LEMP) has now become an important phenomenon in the analysis of lightninginduced overvoltages. In fact, it has been observed that conventional electromagnetic transient (EMT) analyses have always considered direct current injection methods. Nevertheless, experimental and numerical results suggest that electromagnetic field coupling in LEMP is an important phenomenon, especially in substation environments. In fact, it has been observed that most insulation coordination methods, which are based on standard models, do not take into account LEMP effects. The main reason for this is the complexity in modeling LEMP [55].

Ref.	Study Type	Models Compared	Key Quantitative Findings	Key Observation
[20]	EMT-FDTD validation	EMT, EMT+LEMP, FDTD	EMT underestimates voltage; EMT+LEMP agrees with FDTD (≈ within 10%)	LEMP essential for accuracy
[56]	Hybrid modeling	EMT vs EMT+LEMP	Overvoltage increases significantly when LEMP is included	Conventional EMT is non-conservative
[57]	Statistical + EMT analysis	With/without LEMP	Flashover probability increases from **30% to 79.7%**	LEMP drastically increases insulation failure risk
[18]	EMT simulation study	With/without LEMP	Higher flashover occurrence when LEMP is included	LEMP has significant impact in practical systems
[21]	Substation transient study	EMT vs EMT+LEMP	Voltage negligible without LEMP; significant with LEMP	LEMP dominates substation overvoltage behavior
[58]	Numerical electromagnetic study	Field-to-line coupling models	Induced voltage depends on distance and propagation speed	LEMP governs indirect lightning effects

5.1. Modelling Approaches From the Literature

This studies show that in table 3 you can see that LEMP has an impact on how we figure out overvoltage especially when we are talking about back-flashover scenarios. A lot of the research says that the usual EMT models do not do a job of estimating voltage stress. On the hand models that combine different things like electromagnetic coupling give us more accurate results. When we do analyses we find out that the chance of flashover goes up a lot when we take LEMP into account. LEMP is really important, in these situations. We need to consider LEMP when we are trying to understand what is going on with overvoltage and flashover.

Existing studies on LEMP can be broadly categorized into two approaches:

- **Finite-Difference Time-Domain (FDTD) Model**: The Finite-Difference Time-Domain model helps us understand interactions. It solves Maxwells equations directly. This gives a picture of how electromagnetic radiation, coupling and interactions work in lightning channels and substations. This method is very computationally heavy. So it’s not ideal for studies.

- **EMT Model:** Recently EMT-based methods have improved, They now include the effects of LEMP. It helps add voltages to circuit simulations. This balance makes EMT-based methods efficient and accurate. Studies comparing EMT and electromagnetic approaches show that EMT can give results. This reduces burden. The Finite-Difference Time-Domain model and EMT model are tools. The EMT model is more efficient Where, The Finite-Difference Time-Domain model is more accurate. EMT model provides a balance between accuracy and efficiency where, The Finite-Difference Time-Domain model is good for detailed studies.

5.2. Influence of LEMP on Lightning Mechanisms and Voltage Enhancement

One important finding in the literature is that the lightning interaction mechanism has a significant influence on the impact of lightning electromagnetic pulses (LEMPs). Overvoltage are mostly controlled by injected current and subsequent travelling wave propagation in shielding failure (SF) situations, where lightning strikes the phase conductor directly.In these situations, LEMP's contribution is typically minimal because traditional electromagnetic transient (EMT) models already account for the major mechanism. When we talk about back flashover events that happen because of tower strikes LEMP is very important. The electromagnetic fields that are sent out make voltages in conductors and these interact with the waves that are moving because of the lightning current.

Table 4 Comparison of Electromagnetic and EMT-Based Approaches for Lightning Analysis

Approach	Description	Advantages	Limitations
Electromagnetic Methods (FDTD)	Full-wave solution of Maxwell's equations	High accuracy, captures 3D effects	High computational cost
EMT with LEMP Integration	Field-to-line coupling	Efficient, suitable for large systems	Relies on simplifying assumptions

It is worth noting that the voltages caused by LEMP can have the polarity of the surge caused by the current and they can get to the substation before the surge, which makes the waveform get distorted and puts more stress on the insulation. The reason we get overvoltage in these situations is because of how the lightning channel and the conductors near it interact with each other in an electromagnetic way. The electric field that hits the transmission lines makes voltages in them. These are added to the voltages that are made by the direct lightning current. Because the induced and injected parts have polarities they can add up in a way that makes the voltage stress, on the insulation systems even higher. This is especially important when we are dealing with flashover scenarios because both the electromagnetic interaction and the current injection affect how the flashover starts and spreads. So if we do not take LEMP into account in these cases we might underestimate how high the overvoltage can get and not accurately assess how well the insulation is working.

5.3. Interaction with Travelling Waves

Lightning electromagnetic pulse (LEMP) also introduces new voltage components that propagate along the transmission lines, thereby affecting the conventional traveling waves that are generated by the lightning current. These interactions include the superposition of the induced and injected voltages, phase differences, and localized voltage buildup at the impedance discontinuities such as towers and substations. In conclusion, the transient response cannot be determined by a single traveling wave component but by a number of wave components. This implies that the conventional traveling wave-based models may not be used to determine the actual overvoltage in substations, especially in the case of tower-related lightning surges, without considering the electromagnetic pulse effect.

5.4. Limitation

Despite recent efforts to integrate LEMP into EMT frameworks, existing models remain incomplete for two key reasons:

- **Single-stroke assumption**: Nearly all studies assume a single lightning return stroke, ignoring the inherently multi-stroke nature of lightning.
- **Lack of cumulative interaction modeling**: Even when LEMP is included, its interaction with successive strokes is not considered. This creates a disconnect between modeled and real lightning events, where repeated electromagnetic excitation plays a significant role.

5.5. Application

The interaction between LEMP-induced voltages and travelling waves has direct implications for insulation coordination, surge arrester design, and substation layout optimization, as it governs the actual overvoltage distribution within the system

6. Discussion and Critical Analysis

6.1. Critical Analysis of Lightning Current Models

In the selection of lightning current models, a large variation is introduced in calculated overvoltage. This variation is closely related to insulation coordination. In terms of quantifying the variation between the two models, it has been found that the peak overvoltage calculated using the CIGRE model can be 60-70% greater than the peak overvoltage calculated using the Heidler subsequent stroke model and over 400% greater than the peak overvoltage calculated using the first stroke models. The overestimation of calculated overvoltage is mainly due to the simple concave waveform structure of the CIGRE model. This is associated with higher front steepness and higher values of high-frequency content. Although this is beneficial in terms of insulation coordination and surge protection device selection, there is a possibility of over-dimensioning. On the contrary, the Heidler model has better physical accuracy by using continuous waveform representation. However, this comes at the expense of sensitivity to parameter choice. Changes in front time constants as well as peak current parameters may result in overvoltage differing by 20-30%. A major drawback in both models is the single-stroke lightning event assumption. In the real world, it is seen that in multi-stroke lightning, the strokes occur in such a way that the currents have higher steepness, thereby increasing the high-frequency components in the waveform, thereby increasing the voltage. According to the studies done on this topic, the peak overvoltage are underestimated by 30-50%.

6.3. Critical Analysis of Shielding Failure and Back Flashover

Currently, research on lightning-induced overvoltage has addressed shielding failure and back flashover separately under certain assumptions. Nevertheless, such an assumption is not entirely realistic in addressing real system behavior, especially in multiple lightning stroke conditions. The majority of models have adopted single-stroke lightning and constant grounding resistance. These assumptions can cause considerable underestimation of overvoltage. Subsequent lightning strokes have greater current steepness, resulting in stronger high-frequency components and greater wave reflections. These factors cause greater overvoltage. The effect of such overvoltages is not taken into account in conventional models. In addition, it is generally accepted that grounding resistance is not constant; it varies depending on soil conditions and moisture content. These factors affect back flashover performance. Currently, research on lightning-induced overvoltage has addressed shielding failure and back flashover separately. The possibility of interaction between these two phenomena has not been taken into account in addressing real system behavior. The research needs to be extended to include comprehensive models involving multiple lightning strokes, variable grounding conditions, and combined mechanism analysis.

6.4. Critical Analysis of the Back Flashover Reduction Methods

The reviewed investigations provide consistent confirmation that the application of surge arresters significantly reduces the overvoltages created by lightning strikes and decreases the frequency of outages on transmission lines. The actual performance of surge arresters can also depend on different parameters (e.g., tower footing resistance, characteristics of the lightning current, configuration of the transmission line). Many types of optimization techniques have improved surge arrester placement, but most of the works do not have real-world validation because they used either simplifications or simulations instead of accurate measurements. Recent studies have found that surge arresters can cause the "transfer of voltage effect" to occur, resulting in a surge arrester redistributing the overvoltage stress to adjacent towers, which is a limitation that suggests that there is a critical need for additional experimental validation and/or comprehensive models.

6.5. Critical analysis of the Travelling wave Propogation to Substation

Multiple strokes of lightning can produce multiple travelling waves on the transmission lines, in contrast to a single surge of lightning. Each stroke of lightning creates a new travelling wave and transmits it in the direction of the substation. These travelling waves can interact with each other and may result in the formation of a superposition of travelling waves and may even get amplified. This short duration of time between the strokes of lightning makes the analysis of transients more complicated. Each stroke of lightning creates a LEMP, and the LEMP creates travelling waves on the adjacent conductors.

Ref.	Method	Key Findings	Critical Insight
[59]	PSCAD	Arresters reduce overvoltage	Needs real-world validation
[60]	EMTP-RV	Eliminates double outages	Energy rating is critical
[61]	Monte Carlo + ATP	Transfer effect observed	May shift stress to towers
[62]	Statistical+ simulation	High lightning risk	Design affects performance
[63]	EMTP multiphase	Depends on AC & grounding	Simple models underestimate
[64]	Optimization	Reduces outages	Needs practical constraints
[65]	Simulation	Lower resistance helps	Grounding is key factor
[66]	Energy analysis	Repeated surges degrade	Reliability needs study
[67]	PSCAD	Arresters reduce overvoltage	Needs real-world validation

7. Future Research Scope

However, there are still some significant limitations in the analysis of lightning-induced overvoltage. For instance, the majority of the existing analysis is based on single-stroke lightning models. In contrast, in the field of lightning protection, lightning is a multi-stroke process and the overvoltage generated by the later strokes may be higher than those of the preceding strokes. Moreover, the shielding failure and back flashover problems are analyzed separately in the existing analysis. In fact, the two problems are correlated in some aspects because they are both affected by lightning and system characteristics. Another limitation in the existing analysis is the way in which the lightning attachment and grounding problems are handled. In the majority of the existing analysis, the lightning attachment and grounding problems are assumed to be linear and the strike location is assumed to be uncertain. In the analysis of lightning overvoltage in the power systems, the interaction between the transmission lines and the substation is often assumed to be linear with limited reflection of the travelling waves.

8. Recommendation For Modelling

The selection of lightning models should be application-driven. For insulation coordination and routine engineering studies, the CIGRE current model combined with the Electro geometric Model (EGM) is recommended due to its simplicity, standardization, and inherently conservative overvoltage estimation. For research-oriented and high-accuracy transient analysis, the Heidler current model together with the Leader Progression Model (LPM) is more suitable, as it provides a more accurate representation of lightning waveform characteristics and physical attachment processes. In addition, the Lightning Electromagnetic Pulse (LEMP) approach can be effectively incorporated in both insulation coordination and research-oriented studies, particularly for back flashover conditions, where shielding failure has a relatively insignificant impact. This highlights the importance of selecting appropriate modeling techniques based on the specific lightning interaction mechanism being analyzed.

9. Conclusion

This paper proposes a comprehensive approach to the analysis of lightning-induced overvoltage in substations by taking into account the impact of back flashover, lightning electromagnetic pulse, and shielding failure. The paper concluded that back flashover is the dominant factor, whereas shielding failure is mainly dependent on the geometrical configuration, and back flashover is affected by the grounding conditions as well as the voltage. The results show the impact of lightning electromagnetic pulse on the transient response, which affects the waveform by causing voltage amplification. In conventional models, the impact is usually neglected, which could lead to the underestimation of the insulation. In this paper, it is concluded that conventional modeling techniques, such as EGM, EMT, and LPM, are insufficient for analyzing lightning overvoltage, since they do not accurately represent real lightning behavior, owing to their limitations, such as single-stroke assumption and constant grounding resistance. In addition, it is concluded that a holistic, hybrid modeling technique is required for analyzing lightning overvoltages, including all effects of lightning, electromagnetic effects, etc.

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