IJAM: International Journal of Advanced Multidisciplinary
GREENATION PUBLISHER
+62 812 1046 7572 http://greenpub.org greenation.info@gmail.com
DOI: https://doi.org/10.38035/ijam.v4i4

Optimal Placement Analysis of Surge Protective Devices Against Lightning Impulses at Main Distribution Panels Using MATLAB Simulation

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Abstract: Lightning-induced transient overvoltages pose a serious threat to modern electrical installations, particularly at main distribution panels where electrical energy is concentrated. Improper mitigation of these surges may lead to insulation breakdown, equipment damage, and system outages. This paper presents an analysis of the optimal placement of surge protective devices (SPDs) against lightning impulses at the main distribution panel using MATLAB-based simulation. Several protection scenarios are evaluated, including an unprotected condition and various SPD placement configurations. Lightning impulses are modeled using standard impulse waveforms, and system responses are analyzed in the time domain. Simulation results indicate that SPD placement significantly affects residual voltage levels and transient response stability. The optimal configuration is achieved by installing SPDs at the incoming side of the main panel, resulting in the lowest peak residual voltage and the most stable voltage response. The findings provide practical guidance for designing effective surge protection schemes in lightning-prone regions.

Keyword: Lightning impulse, surge protective device (SPD), main distribution panel, transient overvoltage, MATLAB simulation

INTRODUCTION

Lightning-induced transient overvoltages represent one of the most critical external disturbances affecting electrical power systems. These phenomena are characterized by high peak voltages, steep wavefronts, and short durations, which can easily exceed the dielectric withstand capability of electrical and electronic equipment. In low-voltage distribution systems, lightning surges may propagate through power lines, grounding systems, and electromagnetic coupling, causing severe damage to sensitive equipment and compromising system reliability (N. I. Ahmad, M. A. Z. Ab-Kadir, M. Izadi, and N. H. Zaini, 2021), (M. Mohsen, H. A. Zeineldin, and R. M. Shubair,2025).

The main distribution panel is a particularly vulnerable component of electrical installations because it serves as the central node for power distribution to downstream loads. Lightning impulses entering the system through incoming feeders or induced voltages may accumulate at this point and propagate throughout the internal distribution network. International standards such as IEC 62305 and IEEE C62.41 identify the main panel as a critical location with high surge exposure, requiring coordinated surge protection measures (IEC 62305-1)(IEEE Std C62.41.1-2002).

In recent years, the increasing use of power electronics, automation systems, and digital control equipment has significantly increased the susceptibility of electrical installations to transient overvoltages. Devices such as programmable logic controllers (PLCs), variable frequency drives (VFDs), and communication systems have narrow voltage tolerance limits, making them highly sensitive to lightning-induced surges. Consequently, even short-duration overvoltages may lead to insulation degradation, malfunction, or permanent equipment failure (Z. Zhao et al.,2022), (S. Chen, X. Liu, and Y. Zhang,2026).

Surge protective devices (SPDs) are widely applied to mitigate lightning-induced overvoltages by limiting surge voltage levels and diverting surge currents safely to ground. SPDs are generally classified into Type 1, Type 2, and Type 3 according to their application location and surge current handling capability. While standards provide general guidance on SPD classification and coordination, numerous studies have shown that the protective effectiveness of an SPD is strongly influenced by its placement within the electrical system (W. S. Castro, H. S. Castro, and J. L. F. de Carvalho ,2022), (M. Borecki et al ,2023).

Improper SPD placement may result in excessive residual voltage at critical nodes, delayed response to lightning impulses, and reduced overall protection performance. Several researchers have demonstrated that even when SPDs are installed, suboptimal placement can allow damaging voltage levels to reach sensitive equipment (N. Ravichandran, 2024),(F. Safaei et al.,2024). Therefore, determining the optimal placement of SPDs, particularly at the main distribution panel, is a crucial aspect of surge protection system design.

Simulation-based analysis has become an effective approach for evaluating lightning-induced overvoltages and the performance of surge protection schemes. Numerical simulation allows detailed modeling of lightning impulse waveforms, electrical network parameters, and nonlinear SPD characteristics under controlled and repeatable conditions. MATLAB/Simulink has been widely used in transient analysis studies due to its flexibility in modeling time-domain responses and nonlinear components (E. Mohamed ,2023),(M. Banjanin ,2025).

Recent studies have employed MATLAB-based simulation to analyze lightning-induced surges in distribution systems, photovoltaic installations, and energy storage systems. These studies confirm that simulation results provide valuable quantitative insights into peak voltage reduction, residual voltage behavior, and transient response stability for different protection configurations (I. Hetita et al,2022),(M. Soomro et al. ,2024),(Y. H. Kim et al.,2025).However, most existing research focuses on specific applications such as transmission lines, substations, or renewable energy systems, while detailed quantitative evaluation of SPD placement variations at the main distribution panel remains limited.

In lightning-prone regions such as tropical countries, the need for optimized surge protection strategies is particularly critical. High lightning density significantly increases the probability of lightning-induced disturbances, making improper protection design a major risk factor for electrical installations (BouMous et al.,2023),(A. H. K. Asadi et al.,2024). Therefore, a systematic analysis of SPD placement variations at the main distribution panel is required to enhance system reliability and safety.

This paper presents a MATLAB-based simulation study to analyze the effect of various SPD placement configurations on lightning-induced transient overvoltages at the main distribution panel. Several scenarios, including an unprotected system and multiple SPD installation locations, are evaluated and compared in terms of peak overvoltage magnitude and transient response characteristics. The objective of this study is to identify the optimal SPD placement that minimizes residual voltage and improves surge protection effectiveness. The findings are expected to provide practical guidance for the design and implementation of surge protection systems in low-voltage electrical installations exposed to lightning activity.

METHOD

A. Lightning Impulse Modeling

Lightning impulses are modeled using standard impulse waveforms in accordance with international standards. The applied impulse represents a typical lightning-induced transient with a fast rise time and high peak magnitude. The impulse source is injected into the modeled electrical system to evaluate transient voltage responses at the main distribution panel.

B. Main Distribution Panel Model

The main distribution panel is modeled as an equivalent R–L–C network representing busbars, conductors, and connected loads. This model enables time-domain analysis of transient voltage propagation and reflection within the system.

C. Surge Protective Device Modeling

SPDs are modeled as nonlinear voltage-dependent elements representing typical metal oxide varistor (MOV) characteristics. The SPD conducts when the voltage exceeds its clamping level, thereby limiting overvoltage and diverting surge current to ground.

D. Simulation Scenarios

Several scenarios are evaluated:

1. System without surge protection
2. SPD installed at the incoming side of the main panel
3. SPD installed at the main busbar
4. SPD installed along the distribution feeder

RESULTS AND DISCUSSION

Simulation results demonstrate that SPD placement has a significant impact on transient overvoltage behavior. The unprotected system exhibits the highest peak voltage with an unstable waveform, indicating a high risk of equipment damage.

Installing an SPD at the incoming side of the main panel yields the lowest residual voltage and the most stable transient response. Placement at the main busbar and along the distribution feeder reduces overvoltage compared to the unprotected condition; however, residual voltage levels remain higher than those achieved with incoming-side protection.

These results confirm that SPD effectiveness is strongly influenced by its proximity to the surge entry point. Early interception of the lightning impulse at the incoming side prevents excessive voltage propagation into the internal distribution system.

Overvoltage Response with SPD Installation

1. Type 1 SPD Response

Type 1 SPDs are designed to withstand direct lightning currents with a large current-discharge capacity. Simulation results show that Type 1 SPDs can significantly limit the peak voltage when a lightning impulse enters the system. The remaining residual voltage remains relatively high, but at a safer level than without an SPD. The Type 1 SPD response is very fast and effective in containing large-scale impulse energy.

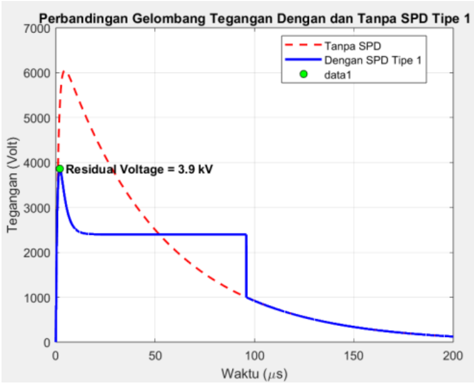

Figure 1. Shows the transient voltage waveform that occurs during installation of a Type 1 SPD.

The effect of SPD installation on transient overvoltage response is shown in Figure 4.6. The graph compares the system voltage response after the SPD is installed compared to the unprotected condition.

According to Figure 1, SPD installation resulted in a significant reduction in peak voltage. The maximum voltage, which initially reached 6 kV, decreased to 3.9 kV after the SPD was operational. This represents a voltage reduction of up to 36%. This indicates that Type 1 SPDs are effective in reducing peak strain. However, the residual voltage remains relatively high, putting sensitive devices at risk of damage.

In addition to the reduced amplitude, the transient waveform also exhibits more damped characteristics. This indicates that the SPD is effective in limiting overvoltage by diverting surge current to the ground system.

2. SPD Response Combination Type 1 and Type 2

The following simulation uses a combination of Type 1 and Type 2 SPDs in a tiered manner (coordinated protection), as recommended by IEC 61643-11. The results of the system simulation with a combination of Type 1 and Type 2 SPDs are shown in Figure 2.

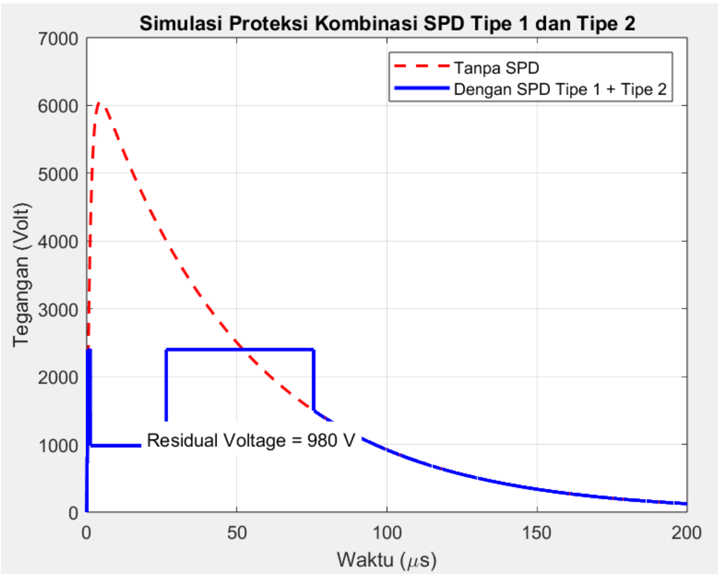

Figure 2. Shows the transient voltage waveform that occurs when installing the Type 1+2 SPD combination.

This configuration produces a residual voltage of 980 V, with a faster impulse damping time than using a single SPD. With an 84.8% reduction in the initial voltage, this configuration begins to meet protection standards for low-voltage components (<1 kV).

Analysis of SPD Placement Variations

To determine the effect of SPD installation location, simulations were conducted with several placement variations. The overvoltage response results for each variation are shown in Figures 3 to 5.

SPD Installed on Incoming Side

The graph in Figure 4.12 shows the voltage response when the SPD is installed on the incoming side of the main panel. The peak voltage measured in this configuration is 2.09 kV, which is the lowest value compared to the other scenarios.

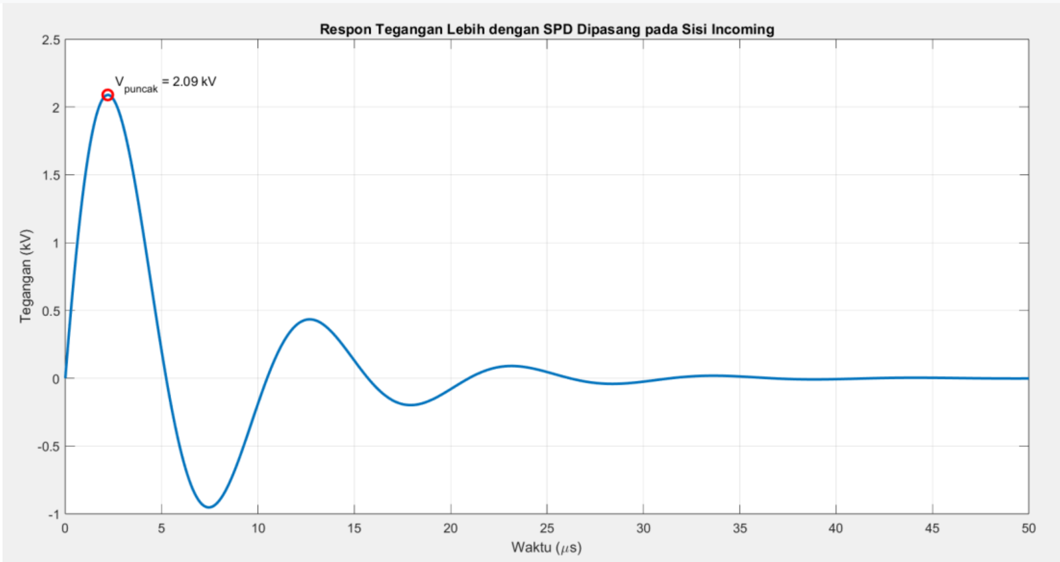

Figure 3. Overvoltage response with SPD installed on the incoming side

The graph in Figure 3 shows the transient overvoltage response when a Type 1 SPD is installed on the incoming side of the main panel. Based on the simulation results, the peak voltage is 2.09 kV, which is the lowest value compared to other SPD placement configurations. This indicates that installing the SPD on the incoming side is able to dampen the lightning impulse energy from the beginning of its entry into the system, thus minimizing the residual voltage transmitted to the main panel.

SPD Installed on the Main Busbar

In the SPD configuration installed on the main busbar, the voltage response is shown in Figure 4. The peak voltage that occurs still experiences a decrease compared to the condition without protection, but the value is higher than the placement on the incoming side.

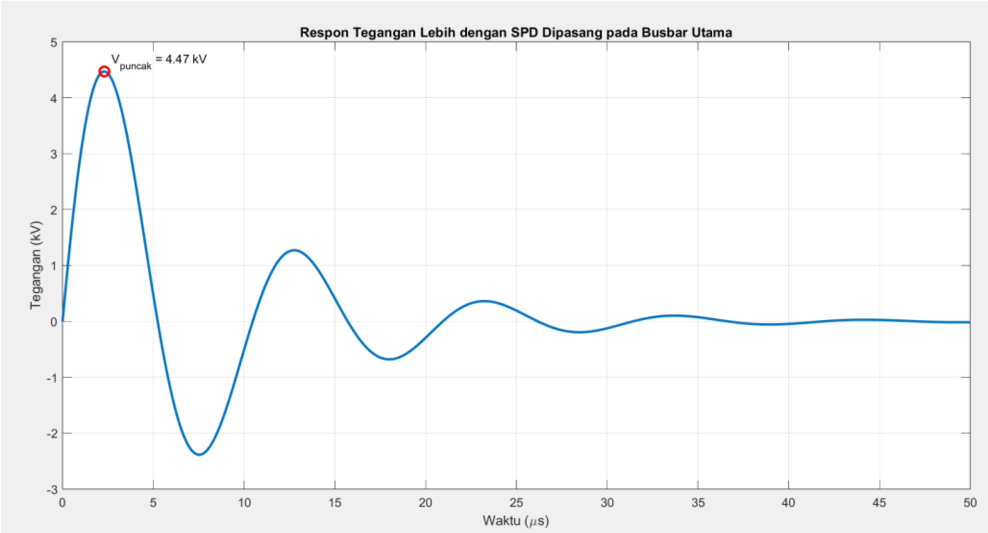

Figure 4. Overvoltage response with SPD installed on the main busbar

The graph in Figure 4.4 shows the transient overvoltage response when an SPD is installed on the main busbar of the main panel. Based on the simulation results, the peak voltage that occurs is 4.47 kV, which is still lower than the condition without protection, but higher than the SPD placement on the incoming side. This indicates that although the SPD on the main busbar is able to reduce the overvoltage, its effectiveness is reduced because some of the lightning impulse energy has already propagated into the system before being limited by the SPD.

SPD Installed on Distribution Lines

The simulation results in Figure 4.5 show that placing the SPD on the distribution line produces the highest residual stress among all scenarios. This is because some of the impulse energy has already propagated to the main panel before being limited by the SPD.

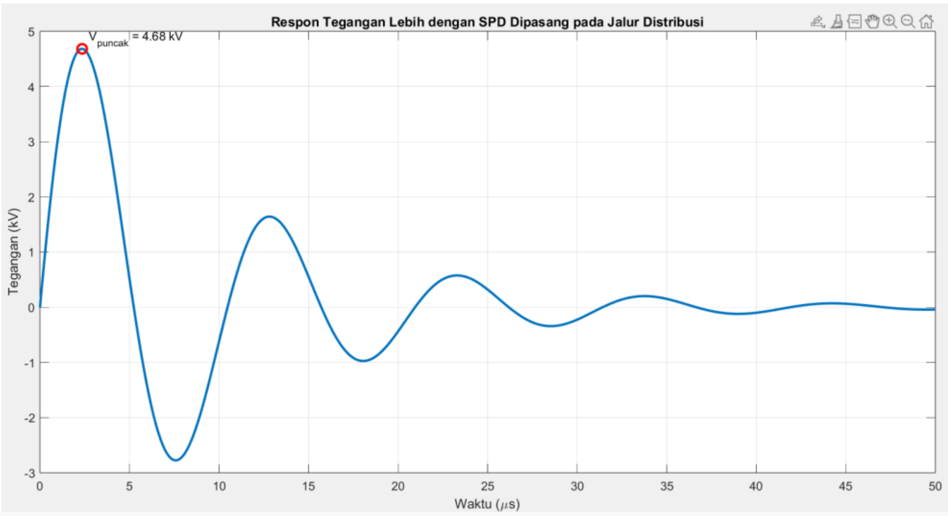

Figure 5. Overvoltage Response with SPD installed on Distribution Line

The graph in Figure 5 shows the transient overvoltage response when an SPD is installed on a distribution line. Based on the simulation results, the measured peak voltage was 4.68 kV, which is the highest value compared to the scenario where the SPD is placed on the incoming side and the main busbar. This is because most of the lightning impulse energy has already traveled to the main panel before being limited by the SPD, resulting in lower damping effectiveness.

Table 1. Comparison and Determination of Optimal SPD Placement

No	SPD Placement Variation	SPD Placement Location	Peak Voltage (kV)	Voltage Response Characteristics
1	No Protection	-	6 kV	Very High voltage, sharp spikes, unstable
2	SPD Type 1	Side Incoming Panel	2.09 kV	Lowest voltage, most stable response
3	SPD Type 1	Main Busbar	4,47 kV	The voltage drops, but there are still surges
4	SPD Type 1	Distribution Channels	4,68 kV	The highest residual stress among the SPD scenarios

A comparison of the peak voltage values of all SPD placement variations is summarized in Table 1. Based on this table, it can be seen that the SPD placement on the incoming side produces the lowest residual voltage and the most stable wave response.

Thus, based on the simulation results shown in Figure 3 and Table 1, the placement of the SPD on the incoming side of the main panel is determined as the most optimal configuration in reducing overvoltage due to lightning impulses.

CONCLUSION

This paper has presented a MATLAB-based simulation study on the optimal placement of surge protective devices against lightning impulses at the main distribution panel. The results indicate that SPD placement significantly affects transient overvoltage magnitude and waveform stability. Among the evaluated configurations, installing the SPD at the incoming side of the main panel provides the most effective protection by achieving the lowest residual voltage and the most stable response. The findings offer practical recommendations for surge protection design and contribute to improved reliability of electrical installations in lightning-prone environments.

Based on the simulation results and comparison of peak voltage values for various SPD placement variations as summarized in Table 1, it can be concluded that SPD placement has a significant influence on the magnitude of transient overvoltages received by the main panel. In unprotected conditions, the peak voltage that occurs reaches 6 kV, showing sharp voltage spikes and unstable system response, thus potentially causing damage to electrical equipment.

The SPDs on the incoming side of the main panel resulted in the lowest peak voltage, at 2.09 kV, and exhibited the most stable voltage response characteristics. This indicates that the most effective lightning impulse damping is achieved when the SPDs are installed as close as possible to the fault entry point into the system.

Meanwhile, the placement of SPDs on the main busbar and distribution lines resulted in peak voltages of 4.47 kV and 4.68 kV, respectively. While both configurations were still able to reduce the voltage compared to the unprotected condition, the residual voltage values were higher than those on the incoming side. This is because some of the lightning impulse energy had already propagated into the system before being limited by the SPD, thus reducing the effectiveness of the damping.

Thus, based on the simulation results, it can be concluded that placing a Type 1 SPD on the incoming side of the main panel is the most optimal configuration in reducing overvoltage due to lightning impulses, in terms of the lowest peak voltage value and system response stability.

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