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Performance Evaluation of surge arrester effectiveness against lightning at Solar & Grid Electrical System

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Abstract: Various government organizations are increasingly integrating their solar farms with utility grids, driven by concerns related to fossil fuels, the economy, and the environment. However, these installations are vulnerable to lightning strikes, both direct and indirect, which can disrupt power supply and damage equipment insulation, also dedicated standards are not available for lightning protection of PV System. To address these challenges, surge arrester effectiveness is conducted to anticipate extreme operating conditions. This research aims to evaluate the system's resilience against transient overvoltages and assess the effectiveness of protection devices in securing solar and grid electrical systems. The study examines different lightning transients impact using PSCAD/EMTDCS Software with pre and post lightning protection system at solar and Grid electrical power system. The performance evaluation will determine insulation stress and surge arrester effectiveness in mitigating lightning transients.

Keywords: *Insulation, Lightning, Lightning Protection device, Simulation*

1. Introduction

Lightning is a natural electrical discharge in the atmosphere, commonly observed during thunderstorms. It occurs due to the interaction of charged clouds in the sky. Lightning can be cloud-to-cloud, intracloud, cloud-to-air, and cloud-to-ground. Approximately 75% of lightning discharges fall into the cloud-to-cloud & intra-cloud and cloud-to-air categories. The remaining 25% comprise cloud-to-ground discharges, which are the most severe and damaging form of lightning. [1] [2]. According to the study, most of transmission line faults result from lightning strikes. Moreover, open areas are susceptible to air humidity & solar radiations factors that increase the frequency of lightning events. [3]. The safe operation of a transmission line is significantly compromised when lightning directly strikes the phase conductor and bypasses the shielding wire. This occurrence leads to the generation of substantial transient overvoltages, posing a serious threat to the system's stability. Lightning induces a significant amount of voltage in the system, propagating in both directions. For instance, if lightning strikes the common coupling point of the solar and grid system (i.e. transformer), voltage traveling waves with magnitudes many times the rated voltage spread in both the solar and grid directions. [1]

In the research analysis, a practical model involving the integration of a utility grid with a solar farm is examined. Within this setup, a 50MW solar farm generates energy at a 33KV solar substation. The generated energy is then elevated through a 50MVA transformer and connected to the 132kV grid. The chosen installation location exposes the solar and grid electrical systems to the risk of lightning strikes year-round. Particularly vulnerable are the exposed components of the 132-33kV electrical system, which are vulnerable to both direct and indirect lightning strikes, especially during the prevalent cloudy weather conditions that persist for most of the year. This situation underscores the importance of implementing robust lightning protection measures. These measures are essential to guarantee the resilience and stability of integrated solar and grid electrical systems.

The research focused on investigating the effects of lightning induced transient overvoltages on the solar grid electrical system. It aimed to analyze the extent to which these transient overvoltages could be reduced through the implementation of proposed surge arresters, adhering to the specified IEC and IEEE standards. Various scenarios were devised to apply lightning-induced transient overvoltages, allowing for a thorough assessment of the system's effectiveness. These simulations were instrumental in determining the insulation strength of the entire system under different voltage stress conditions, providing valuable insights for the study.

Moreover, this study investigated into the assessment of lightning arrester installations, evaluating how optimized overvoltage protection could be achieved through surge arrestors installed in both the 33kV and 132kV solar and grid electrical systems. The power flow software, PSCAD, was utilized to construct the model, meticulously incorporating nine selected lightning arrester locations. To examine the effectiveness of the proposed surge arresters in meeting the required insulation coordination standards, two distinct cases or scenarios created. These scenarios were conducted with various solar farms integrated into the utility grid via a step-up transformer operating at 132/33 kV. All scenarios were meticulously analyzed, particularly focusing on the worst overvoltage situations, where various components such as supply sources, transmission lines, transformers, solar substation switchgear, feeders, inverter duty transformers, and cables in the focal region might be affected or damaged.

A notable issue arises from the absence of precise standards for lightning protection in PV systems. Current

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guidance is available through documents like German DIN EN 62305-3 (Supplement 5) & Malaysia's MS 1837 guidelines [2] [3]. However, the lack of clearly defined standards creates challenges for implementing Lightning Protection Systems (LPS) in PV systems. This underscores the necessity for comprehensive study of whole system like performed in this study.

In conclusion, the research affirms the feasibility of installing Lightning/Surge Arresters in solar grid electrical systems, aligning with electrical grid regulations. The implementation of surge arresters proves effective in mitigating the impact of overvoltages arising from various potential scenarios, as thoroughly discussed and simulated in this research paper. This finding underscores the significance of these installations in ensuring the stability and reliability of solar grid electrical systems under diverse operational conditions.

This analysis was carried out employing methodologies outlined in the application guides such as IEEE 1313.2, IEEE C62.22, and Insulation Coordination of Power Systems [4][5]. Additionally, the study utilized PSCAD software, a time-domain-based transient software, to accurately assess voltage stresses during surge and switching events. By integrating these established techniques and advanced software tools, the research ensured a comprehensive and precise evaluation of the system's response to various scenarios, providing valuable insights into the effectiveness of surge arresters in managing voltage stresses in solar grid electrical systems.

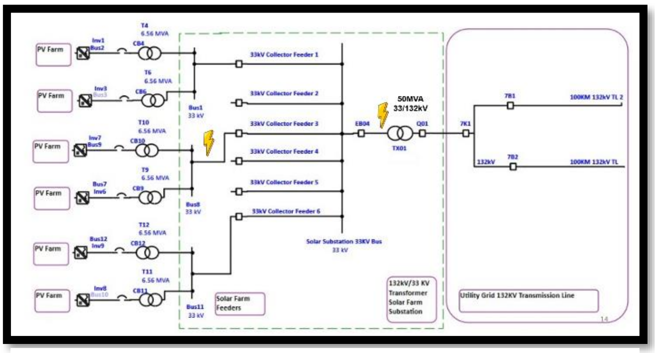


Figure 1:Schematic overview of solar farms integrated with the utility grid via a 132 kV overhead transmission line.

Figure 1 provides a schematic overview of solar farms integrated with the utility grid via a 132 kV overhead transmission line. In this setup, the solar substation plays a pivotal role in gathering power generated by all solar arrays within the solar farms. This aggregated power undergoes an elevation in voltage to 132 kV through the 50MVA Transformer. Subsequently, it is directed into the grid through the 33 kV solar substation. It's important to note that the power flow occurs from the lower section towards the utility grid, specifically originating from the 33 kV bus and flowing into the 132 kV Grid Transmission line.

2. Related Work

Study [6] explores the voltage magnitude at substation transformer when lightning hit the 132kV transmission line. In the study effectiveness of substation surge arrester not evaluated. The study [7] presents a Simulation model which analyze Shielding Failure at 132KV Utility Grid Connected with Windfarm substations, the impact of the Fast front Lightning transient Overvoltages assessed at TL with & without Surge arrester protection, study does not carry out effectiveness and optimization check at Surge Arrester (SA) in mitigating the surge impact at Renewable side. In simulation study model [8][9] analyzed Lightning impact at large scale grid connected Solar System, The study considered impact of different lightning current on PV Side equipment's like Array Modules, Transformers and Inverters. The study suggested to use Surge Protection Device SPD for mitigating the lightning impact, study only considered lightning impact at PV Side only, also complete integrated grid Surge Arrester (SA) effectiveness not also assessed at Utility and Solar Integration point. The simulation study [10] primarily focuses on investigating switching overvoltages that occur across utility grids. However, it falls short in several crucial areas. The study overlooks the evaluation of surge arrester effectiveness in mitigating the impact on the utility grid integrated with renewable energy sources. Furthermore, the study does not investigate scenarios where lightning events coincide with switching operations within the system, leaving a significant gap in understanding the system's response under such simultaneous events. In simulation study [11] examined the impact of lightning on the Utility Grid integrated with a Solar Farm. Various configurations were taken into account, including changes in cable cross-sectional area, length, and soil resistivity. The conclusion drawn was that lightning strikes, regardless of these different configurations, had nearly the same effect and were equally dangerous to the system, also in simulation model surge arrester protection operation was not taken into account. In Simulation study [12] which analyzed lightning impact at Hybrid PV and Wind system using PSCAD Software, specifically focusing on the DC side of the inverters. However, it's important to note that other areas within the hybrid power system were not taken into consideration during the study, also transient over voltage conditions not analyzed at Solar-Grid Integration point. In theoretical research study [13] which investigates the lightning transient impact at PV plant when Lightning event occurs at nearby Transmission line. The study considered different scenarios, investigated the impact of direct and indirect strikes, and assessed impact at diodes, inverters, and solar structure, study only considered impact at PV Side. Lightning impacts not analyzed at Utility and Solar Integration point. The simulation study [14] concentrates solely on lightning effects on the transmission line side, neglecting its impact on other areas within the system. In the study [15], the exclusive focus is on the standards and guidelines essential for lightning protection in PV systems. However, the research overlooks other critical areas within solar integrated setups. Key components such as the impact on solar collector feeders, inverter duty transformers, and solar substations remain unaddressed. The simulation study [16] focused on assessing the lightning surge effects on small-scale rooftop PV systems, yet it failed to analyze other critical voltage transient issues such as switching and ground faults. Additionally, the study did not evaluate the effectiveness of Surge Protective Devices (SPD) in mitigating these transients.

This study is examining the repercussions of lightning strikes on both the solar and grid electrical systems, with a specific emphasis on analyzing the impact at the Solar and Grid common coupling point (33/132kV Transformer) and the 33kV Solar Collector feeder. Additionally, study assessed the efficiency of lightning protection devices, specifically surge arresters, in safeguarding the Utility grid Power system integrated with the solar farm. By focusing on these specific areas, our research aimed to provide valuable insights into the system's vulnerability and the effectiveness of protective measures in the face of lightning-induced challenges.

3. Modelling Lightning Waveshape:

To analyze short duration phenomena within an electrical circuit, the primary method involves solving the relevant system's differential equations. PSCAD software is specifically designed to effectively handle these differential equations, enabling the visualization of rapid transient effects on various electrical parameters within the system. [17]. Different mathematical expressions can be utilized to describe the shapes of lightning currents. In accordance with IEC-62305-1:2010 [18], the Heidler function & double exponential are two common mathematical model employed for analyzing the lightning effect. Specifically, in this PSCAD Based study, the double exponential equation used. Simulation program to generate the impulse lightning wave, enabling a detailed simulation and analysis of the impact of lightning currents on the electrical system. These mathematical models play a crucial role in understanding and predicting the behavior of lightning-induced phenomena within the context of electrical simulations.

$$i(t) = I(e^{-\alpha t} - e^{-\beta t})$$

Here, I =Peak current, α and β = Constants to define the lightning current's waveform tail & front time

In the PSCAD Software, a lightning impulse voltage of 100 MV and 133 kA is generated and applied for the analysis of lightning impact. In the study, a scenario is assumed where the lightning strike bypasses the shielding wire and directly hits the phase conductor, signifying a shielding failure. This specific condition allows for a comprehensive examination of the system's response to lightning-induced transients, considering the potential vulnerabilities and risks associated with such direct strikes on the electrical components. By simulating this scenario, the study aims to gain valuable insights into the system's behavior and assess its resilience under realistic lightning-related conditions.

4. Validation:

In compliance with IEC 60071.1:2019, every piece of equipment is designed to withstand a certain level of overvoltage. Over voltage stress result which obtained from the PSCAD Program evaluated with equipment withstand voltage levels (LIWV) also called BIL Basic impulsive insulation level of equipment and assessed protection system effectiveness in mitigating the stress, in the PSCAD Simulation model, following two cases are developed

Case 1: Lightning at 33kV side of 50MVA Transformer
Case 2: Lightning at 33kV Solar collector feeder

5. Lightning Protection system

At following locations Lightning Protection system LPS are installed, Assessment & effectiveness of these arrester is evaluated in this study work

At 132kV Transmission Line circuit-1/2
At 50MVA Transformer -132kV Side
At 50MVA Transformer -33kV Side
At Solar Collector Feeders – 33kV

At 132kV System surge arrestor ratings
Maximum system voltage –132kV: 145kV
Maximum Continuous operating voltage - MCOV : 145/√3 = 83.7kV

At 33kV System surge arrestor ratings SA
Maximum system voltage –33kV: 36kV
Maximum Continuous operating voltage - MCOV : 36/√3 = 20.78kV

An analytical study has been conducted to evaluate the arrester's energy absorption capacity while discharging lightning currents. This assessment entails comparing the Lightning Impulse Withstand Voltage (LIWV) or BIL of the equipment with the simulated results. By analyzing these parameters, the study aims to determine the arrester's effectiveness, providing valuable insights into the system's resilience against high voltage transient events.[6]

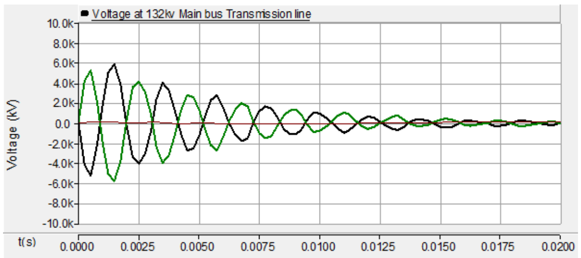
6. Simulation results

6.1 Lightning at 50MVA Transformer (33kV)

In this case, Lightning impulsive voltage of magnitude 100 MV and 133 kA is applied at 50MVA Transformer 33kV Side phase conductors (shielding failure), thru PSCAD simulation system response assessed with pre and post Lighting protection system.
To figure out the behavior of whole system and to assess the insulation stress from Solar to utility grid during the lightning event analysis are made at different points like given below.

- 132kV Transmission line
- 132kV side of 50MVA Transformer
- 33kV side of 50MVA Transformer
- 33 kV solar collector feeder
- Inverter Duty Transformer (IDT)
- Inverter (AC side) Solar Farm

Figure 2 depicts the repercussions of lightning and voltage stress in the absence of surge arrester protection within the solar and grid electrical system. The simulation results expose that there is a notable voltage rise surpassing the equipment's Basic Insulation Level (BIL) Rating. Specifically, in figure (a) the voltage rise at the 132kV transmission line and the 132kV side of the 50MVA transformer registers approximately 6MV. Similarly, at locations (b and c) which encompass the 33kV side of the 50MVA transformer, Solar Collector Feeder (33kV Solar Substation) & Voltage at Inverter Duty Transformer (IDT) (33kV Side) and voltage rise of about 100MV observed at these location. Likewise, in figure (d) Voltage at ac side of Solar Farm inverter exceeds the BIL Rating, BIL Rating is 6kV but voltage found around 167kV without lightning surge arrestor. Please refer Table-1 for summary



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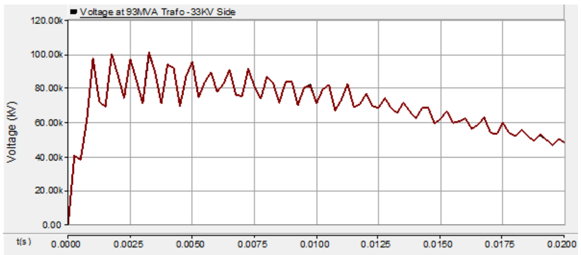

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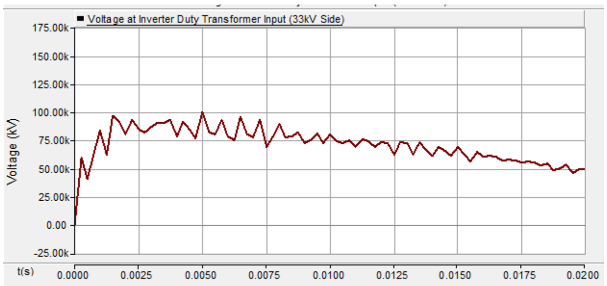

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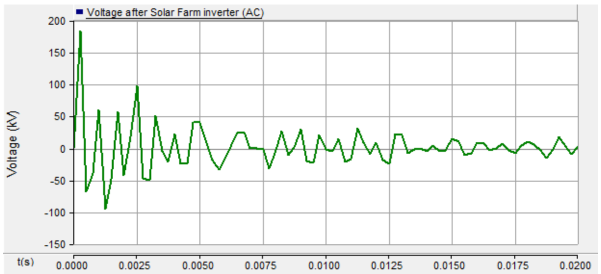

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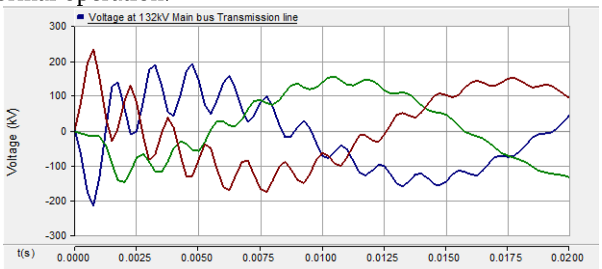
Figure 2. in absence of surge arrester protection voltage rise observed more than BIL Rating of equipment's (a) Voltage at 132kV Transmission line and 132kV side of 50MVA Transformer (b) Voltage at 50MVA Transformer 33kV side and at Solar Collector Feeder (c) Voltage at Inverter Duty Transformer (IDT) (33kV Side); (d) Voltage at Solar Farm inverter (AC side)

Figure 3 depicts the analysis of voltage stress under different scenarios like one with a lightning protection system installed solely on the 33kV side and no surge arrestor considered at 132kV side including at transmission end. The simulation results show that the voltages remain below the Basic Insulation Level (BIL) rating for various equipment. For instance, in figure (a) the voltage at the 132kV side of the transformer and the transmission line observed around 232kV. Similarly, in figure (b and c) which represents 33kV side of 50MVA transformer, solar collector feeder, and solar farm inverter duty transformer, the voltage rise observed around 126kV. The voltage rise at ac side of the Solar Farm inverter observed around 2.2kV and these all result obtained while lightning arrestor considered at 33kV electrical system only.

Figure 4 illustrates the analysis of voltage stress in a scenario where lightning protection surge arrestors are installed throughout the 33kV and 132kV electrical system. The simulation outcomes indicate that the inclusion of surge arrestors successfully mitigates all forms of insulation stress concerns. As a result, the system behaves within expected parameters at all six analysis locations, demonstrating normal operation.



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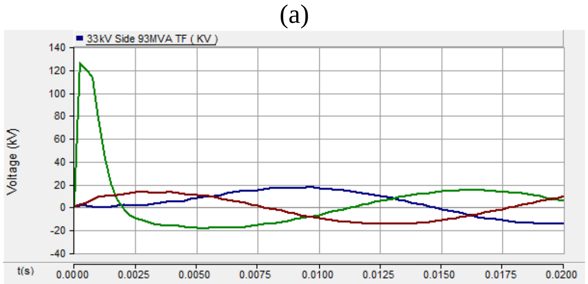

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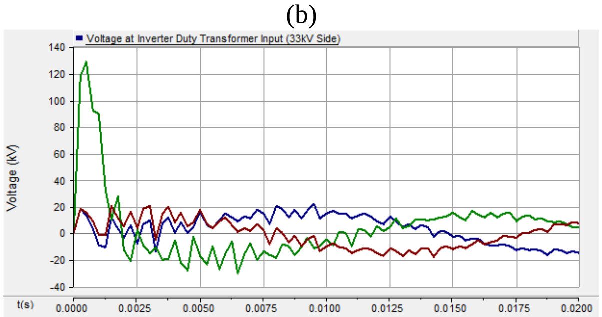

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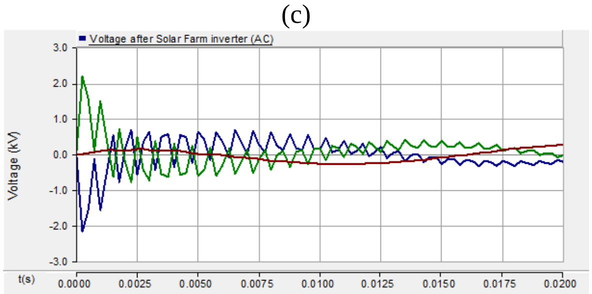
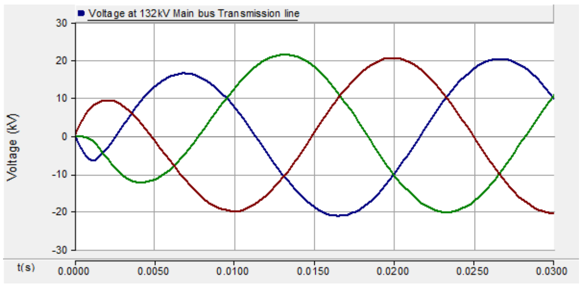


(d)

Figure 3. in this case surge arrester's protection installed at 33kV electrical system (a) Voltage at 132kV Main bus Transmission line and 132kV side of 50MVA Transformer (b) Voltage at 50MVA Transformer 33kV side and at Solar Collector Feeder (33kV Solar Substation) (c) Voltage at Inverter Duty Transformer (IDT) (33kV Side); (d) Voltage at Solar Farm inverter (AC side)



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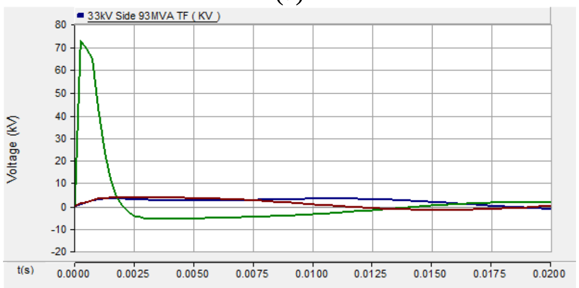

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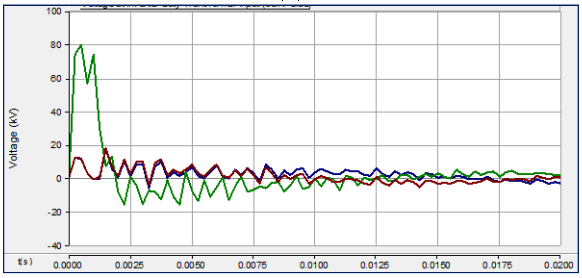

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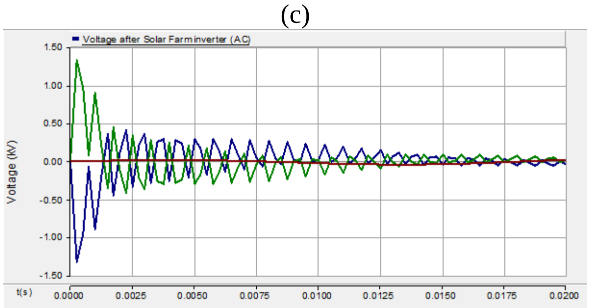


(d)

Figure 4. With all surge arresters installed at 33kV and 132kV electrical system voltage rise observed below the BIL Rating (a) Voltage at 132kV Main bus Transmission line and 132kV side of 50MVA Transformer (b) Voltage at 50MVA Transformer 33kV side and at Solar Collector Feeder (33kV Solar Substation) (c) Voltage at Inverter Duty Transformer (IDT) (33kV Side); (d) Voltage after Solar Farm inverter (AC side)

Table 1: Summary of case 1 result (Lightning at 33kV side of 50MVA Transformer)

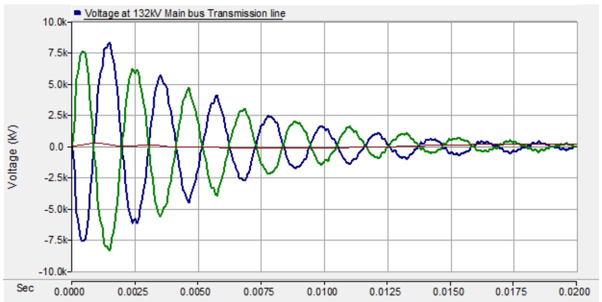
System Places Understudy	**BIL (kV)**	**Without SA Voltage Rise**	**With SA at 33kV Voltage Rise**	**With SA at 132kV 33kV Voltage Rise**
132kV Grid TL	650	6MV	232kV	132kV
50MVA Trafo - 132KV Side	650	6MV	232kV	132kV
50MVA Trafo - 33KV Side	170	100MV	130kV	72kV
33kV Solar Collector Feeder	170	100MV	126kV	72kV

IDT (33kV Side)	170	100MV	126kV	80kV
Inverter (AC)	6	167kV	2.2kV	1.3kV

6.2 Lightning strike at 33kV Solar collector feeder

In this case, Lightning strike is applied at 33KV Solar collector feeder which is installed at solar substation and collecting the energy from the solar farm, in PSCAD simulation evaluated the system behavior with and without applying surge arrester in the system.

Figure 5 illustrates the consequences of lightning and voltage stress when surge arrester protection is absent in the solar and grid electrical system and lightning impact applied at one solar substation collector feeder. The simulation results reveal a significant voltage increase that surpasses the BIL rating of the equipment. In scenarios (a) the surge at 132kV transmission line and the 132kV side of the 50MVA transformer measures approximately 8.3MV. Similarly, at locations (b and c), covering the solar collector feeder at Solar substation, 33kV side of the 50MVA transformer and the solar farm inverter duty transformer, a voltage rise of about 105MV is observed. Furthermore, in figure (d) voltage at solar Farm inverter (AC side) exceeds the BIL rating & found around 400kV without lightning surge arrestor. Further details of results are shared in Table-2



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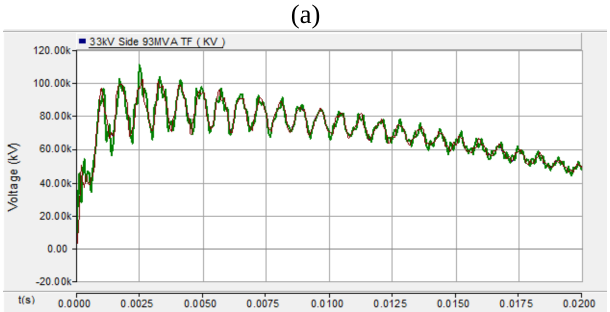

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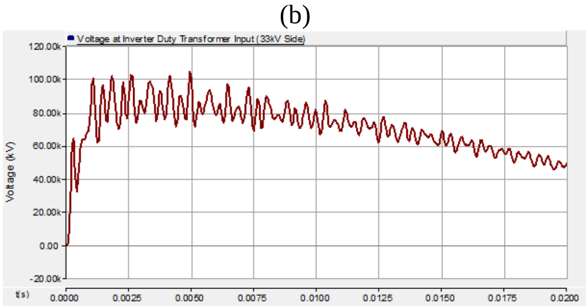

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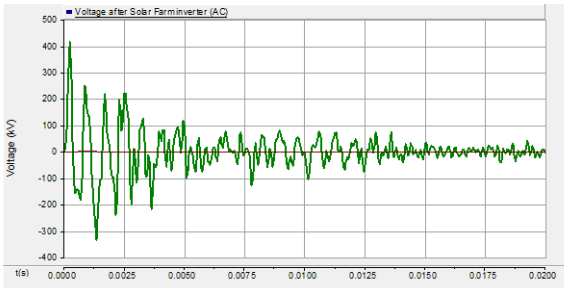

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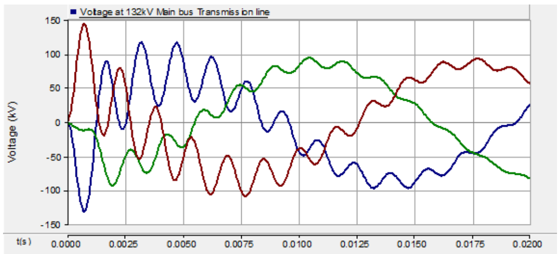
Figure 5. in absence of surge arrester protection voltage rise observed more than BIL Rating of equipment's at Solar and Grid electrical system (a) Voltage at 132kV Main bus Transmission line (b) Voltage at Solar Collector Feeder (33kV Solar Substation) (c) Voltage at Inverter Duty Transformer (IDT) (33kV Side); (d) Voltage after Solar Farm inverter (AC side)

Figure 6 illustrates the examination of voltage stress across different scenarios, such as one where a lightning protection system is exclusively installed on the 33kV side, and no surge arrestors are implemented on the 132kV side (Transmission line end). The simulation outcomes indicate that if lightning strikes the solar substation collector feeder, the voltages remain within acceptable limits as defined by the Basic Insulation Level (BIL) rating for various equipment. For instance, in figure (a) the voltage at 132KV Grid side transmission line and Transformer high voltage side is approximately 200kV. Similarly, in figure (b) which covers 33kV side of 50MVA Transformer and 33kV solar substation, voltage observed 80kV, similarly at 33kV side of inverter duty transformer voltage observed within BIL rating. The voltage at the AC side of solar farm inverter found 2.0kV.



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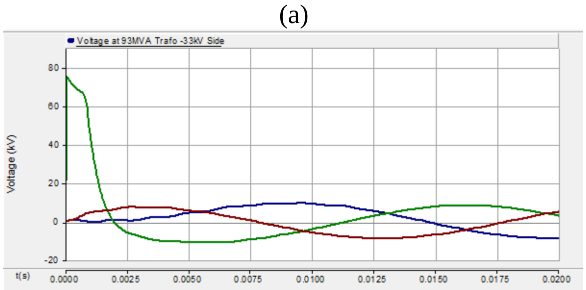

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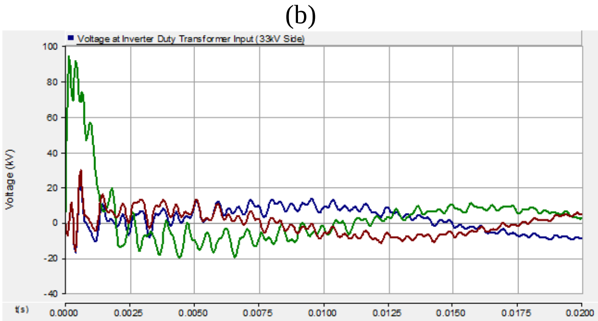

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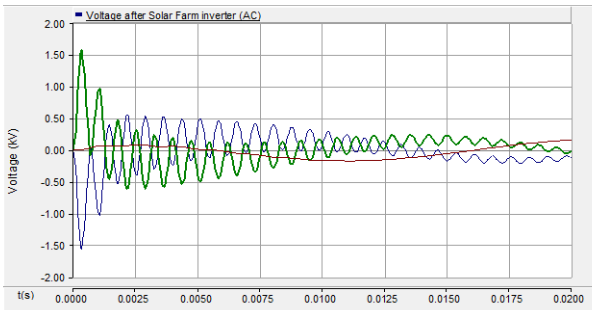

(d)

Figure 6. In this case surge arrester's installed at 33kV electrical system and Lightning applied at one solar collector feeder and impact of this lightning observed at different location of the plant. (a) Voltage at 132kV Main bus Transmission line (b) Voltage at Solar Collector Feeder (33kV Solar Substation) (c) Voltage at Inverter Duty Transformer (IDT) (33kV Side); (d) Voltage after Solar Farm inverter (AC side)

Table 2: Summary of case 2 simulation result (Lightning strike at 33kV Solar collector feeder)

System Places Understudy	**BIL (kV)**	**Without SA Voltage Rise**	**With SA at 33kV Voltage Rise**	**With SA at 132kV 33kV Voltage Rise**
132kV Grid TL	650	8.3 MV	150kV	132kV
50MVA Trafo - 132KV Side	650	8.3 MV	150kV	132kV
50MVA Trafo - 33KV Side	170	105 MV	74kV	130kV
33kV Solar Collector Feeder	170	105 MV	70kV	130kV
IDT (33kV Side)	170	105 MV	95kV	25kV
Inverter (AC)	6	105 kV	1.6kV	2.5kV

5. Conclusion

The integration of a utility grid with a solar farm underscores the need for thorough evaluation of lightning protection system. This proactive approach is vital to avert scenarios like insulation breakdown, flashovers, and other electrical irregularities, all of which could potentially undermine the reliability of the entire system. In this research paper, an investigation conducted to analyze the impact of Fast-Front Overvoltages (FFO), also known as lightning overvoltage, on the Solar and Utility Grid Electrical Power System. The study made use of the PSCAD/EMTDCS software to perform a comprehensive analysis, both before and after the implementation of a Lightning Protection System (LPS). Additionally, the research evaluated the effectiveness of the protection system in safeguarding the system against voltage stress induced by lightning events. Two distinct scenarios created: one involving the application of lightning at the 50MVA Transformer and the other at the solar collector feeder. Through simulations, it is discovered that transient overvoltages have a detrimental impact in situations where lightning surge arresters are absent. These overvoltages are significant enough to cause insulation breakdown and damage interconnected components within the solar and grid electrical systems. To address this issue, surge arresters installed at nine proposed positions throughout the solar and grid electrical system. Their effectiveness in mitigating induced transients evaluated. The research findings demonstrated that when lightning strikes the system, the resulting lightning surges traveled to the solar substation and transmission line through transformers. This phenomenon generated high voltages, posing a potential risk to the safety of power equipment and insulation within the system. However, the implemented lightning surge arresters proved to be highly effective in minimizing the significant overvoltages at the 33kV solar substation and the 132kV transmission line. The study concluded that the selected Surge Arresters in the system are properly designed and functioned in accordance with the system requirements. They successfully met the insulation coordination needs of the Solar and Grid electrical power system, ensuring its resilience and reliability against lightning-induced events. The study holds significance across various aspects, including the design phase, technical evaluation, and sensitivity analysis of lightning transients. It also addresses concerns related to insulation coordination and system reliability. It is noteworthy that this type of insulation coordination study focused on solar and utility grid electrical systems has not been previously reported and is pioneered by this research study. However, it's important to note that the design and selection of lightning arresters were not within the scope of the study

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