

Insulation Coordination of 230KV Gas Insulated Substation Using Power System Tool PSCAD™/EMTDC®

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ABSTRACT: This research explores insulation coordination in a 230 kV GIS using advanced power system simulation tools. Unlike traditional Medium Voltage (MV) systems with conservative insulation designs, High Voltage GIS installations require precise assessment of insulation performance under various transient conditions. Lightning and switching surges are critical factors influencing GIS insulation integrity. The study simulates over-voltage events to optimize insulation levels and strategically position protective devices. A significant aspect of this approach is the use of MOSA, which offer rapid response and high energy absorption during transient events. MOSAs, primarily made of zinc oxide (ZnO), surpass older spark gap-based Arresters due to their nonlinear voltage-current characteristics and self-restoring capability. This research aims to enhance the reliability and longevity of GIS installations by ensuring effective insulation coordination and protection against over-voltage threats.

Keywords: Insulation, Medium Voltage, Lightning, MOSA - Metal Oxide Surge Arresters, Transient Analysis, Gas Insulated Substation, Switching.

1. Introduction

Transient over-voltages are brief, high-magnitude voltage spikes that occur in power systems due to various disturbances. These over-voltages can originate from external sources, such as lightning strikes, or internal events like switching operations, fault clearing, or load rejections. While switching-induced transients are more common, lightning-induced transients are particularly hazardous due to their high energy content and rapid rise time. To mitigate the effects of these over-voltages, surge Arresters are employed. These devices safely divert excess energy to the ground, limiting the voltage to acceptable levels and protecting electrical equipment. However, designing insulation systems to withstand all possible transient over-voltages would be inefficient and economically impractical. Conversely, designing insulation solely for typical

operating voltages without considering transients could lead to frequent insulation failures and equipment damage.

To strike a balance, the concept of insulation coordination is utilized. This involves selecting appropriate insulation levels and protective devices to ensure that surge Arresters operate before the insulation is over stressed. By evaluating the insulation's ability to withstand voltage and ensuring that protective devices activate at voltages below insulation breakdown levels, insulation coordination provides sufficient protection against likely over-voltages without over designing the insulation system. Comprehensive transient analysis and risk assessment are essential to determine anticipated over-voltage magnitudes and frequencies.

This paper proposes an insulation-coordinated protection strategy combined with advanced transient mitigation techniques tailored for modern power systems. The approach involves analyzing the behavior of switching and lightning-induced over-voltages and strategically placing surge Arresters based on system configuration and grounding procedures. Optimal placement and selection of surge protection devices are considered for both indoor and outdoor settings, especially for systems undergoing upgrades or operating under unique configurations. This coordinated approach ensures technical robustness and economic efficiency by enhancing medium-voltage systems' resistance to fast-front and slow-front transients without necessitating overly robust insulation designs. The proposed framework aims to contribute to the development of secure, reliable, and future-proof power distribution infrastructures, facilitating the integration of sensitive electronic devices and renewable energy components.

2. Recent Works

Safaei et al 2024 [11] presents for high-voltage substations have emphasized the importance of environmental factors in optimizing protection strategies. A notable method integrates detailed modeling of transient behaviors in substation components and transmission lines, accounting for environmental conditions such as lightning back flash-overs and switching over-voltages. The method lies in its efficiency and precision in determining optimal Arresters locations, thereby enhancing system reliability while reducing equipment costs. However, a potential demerit is its reliance on accurate environmental data and system parameters; any discrepancies in these inputs affect the method's effectiveness.

Haliloglu et al 2023 [12] depicts the optimized surge Arresters placement for lightning protection in Voltage Source Converter (VSC)-based High Voltage Direct Current (HVDC) prototypes. Utilizing PSCAD simulations, researchers modeled lightning impulses at various points

within the HVDC system to analyze responses and determine effective protection strategies. This approach is its efficiency in enhancing system reliability through targeted protection. However, a potential drawback is the method's reliance on accurate system modeling; any discrepancies in simulation parameters could affect the effectiveness of the protection strategy.

Adenekan et al 2024 [13] represents the application of frequency and time series analysis to evaluate the performance of surge Arresters in power distribution systems. The approach is its ability to provide a comprehensive understanding of surge Arresters behavior, enhancing their effectiveness in voltage surge protection. However, a potential demerit is the reliance on accurate and high-resolution data; any inaccuracies in the data lead to misleading conclusions.

Zhong et al 2024 [14] presents a novel diagnostic framework for 100 kV ultra-high-voltage (UHV) surge Arresters. The approach is its enhanced diagnostic precision, enabling timely maintenance and improved system reliability. However, a potential demerit is the complexity and cost associated with implementing wireless sensor networks in high-voltage environments.

Moghbeli et al 2024 [15] demonstrates Voltage Source Converter (VSC)-based High Voltage Direct Current (HVDC) prototypes, surge Arresters play a pivotal role in limiting voltage stress at DC breakers. The strategic placement of surge Arresters in this design significantly improves the breaker's ability to handle fault conditions by providing an alternative path for fault current. However, this approach is the continuous exposure of the surge Arresters to the source voltage.

By concerning existing systems, the novel contribution introduced in this paper is:

- To simulate lightning and switching transients affecting a 230kV GIS using advanced power system tools.

- To perform customized transient evaluations tailored to indoor GIS configurations, which differ significantly from outdoor setups.
- To optimize the selection and placement of surge Arresters for effective mitigation of fast-front and lightning-induced over voltages.
- To establish a reliable method for reassessing insulation coordination during system upgrades or equipment additions.

3. Proposed Work Explanation

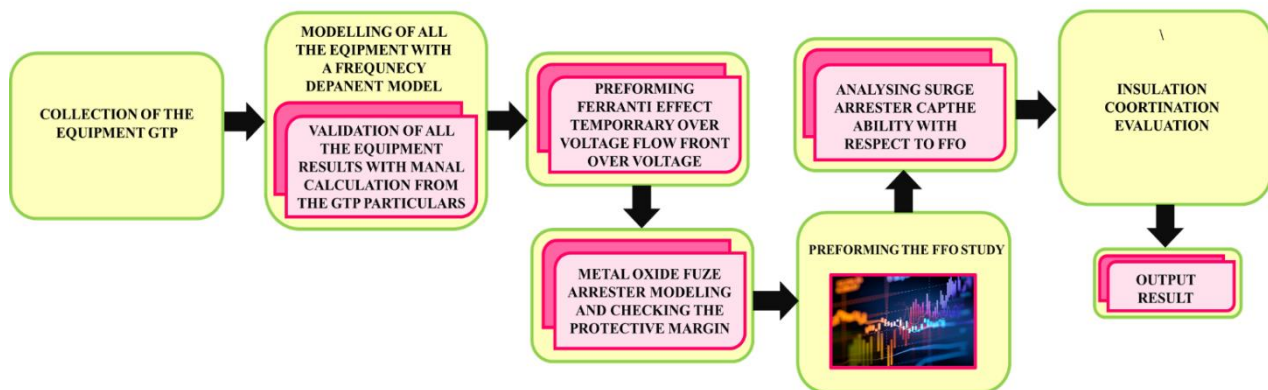


Figure 1: Proposed Block Diagram

Figure 1 illustrates lightning analysis for a 230kV GIS using a simulation-based approach that integrates critical input parameters and advanced modeling. Inputs include lightning impulse magnitude, frequency-dependent line model properties, surge Arresters specifications, and GIS configuration. The frequency-dependent line model is essential for capturing fast transient behaviors caused by lightning. Insulation coordination evaluation ensures insulation levels are appropriately rated against predicted over-voltages. TRV analysis assesses circuit breaker recovery post-fault. The compact GIS structure demands precise modeling of internal reflections. Outputs such as peak over-voltages, Arresters energy absorption, and insulation margins validate system protection and operational reliability.

3.1 System Modeling

Due to the increasing complexity of high-voltage power systems, insulation coordination has become a critical focus in substation design, particularly for 230kV GIS. Traditional design methods are now being enhanced using power system simulation tools to accurately assess insulation stress under various fault and operating conditions. To address these challenges, a new methodology has been developed that employs simulation-based analysis using power system tools, enabling precise coordination of insulation levels and optimal placement of surge protection devices.

3.1.1 Gas Insulated Substations

A GIS is a type of electrical substation in which the major components of the power system are enclosed within a sealed environment filled with sulfur Hexa-fluoride (SF_6) gas, which is used for its excellent dielectric (insulating) and arc-quenching properties.

The major components of a GIS include

Circuit breaker - Circuit breakers are among the most critical components of switch-gear systems. Their high degree of flexibility plays a significant role in the overall design of substations often enabling substantial space savings.

Grounding Disconnector - Two distinct types of enclosed modules line disconnector and grounding disconnector are designed to be integrated within a closed block system.

Cable unit and bushings - Any type of cable whether XLPE or liquid-filled is connected to the GIS through specialized cable termination units.

Current and voltage transformers - For measurement and protection purposes, single-phase current and voltage transformers are commonly used in GIS systems. In some modern applications, three-phase current and voltage sensors are also employed for improved efficiency and compactness.

Control and monitoring - The conventional local control cabinet houses all auxiliary electrical components required for control, signaling, and interconnection within the GIS system.

3.1.2 Metal Oxide Surge Arresters (Mosa)

A MOSA plays a crucial role in protecting electrical systems from transient over-voltages caused by lightning, switching operations, and faults. Unlike conventional spark gap Arresters, MOSAs employ metal oxide varistors (MOVs), mainly made of zinc oxide (ZnO), which exhibit a highly nonlinear current-voltage response. During normal voltage conditions, the Arresters remains non-conductive, permitting only a very small leakage current. When a voltage surge occurs, the MOVs conduct instantly, diverting excess energy to the ground and preventing equipment damage. Once the surge passes, the Arresters automatically returns to its original non-conductive state. This self-healing ability, along with excellent energy absorption and rapid response characteristics, makes MOSAs exceptionally reliable and efficient in modern power networks.

3.1.3 Frequency Dependent Line Model

In the insulation coordination of a 230 kV GIS, precise simulation of electromagnetic transients is essential to ensure insulation can withstand over-voltages from lightning, switching, or faults. The FDLM is a highly accurate method used for simulating such transients in interconnected transmission lines and cables. Unlike constant-parameter models, FDLM considers the

frequency-dependent behavior of resistance, inductance, and capacitance. This is crucial during high-frequency transients, where the skin effect, proximity effect, and ground return path variations significantly influence wave propagation and attenuation. These factors directly impact the insulation's ability to handle transient over-voltage stress effectively.

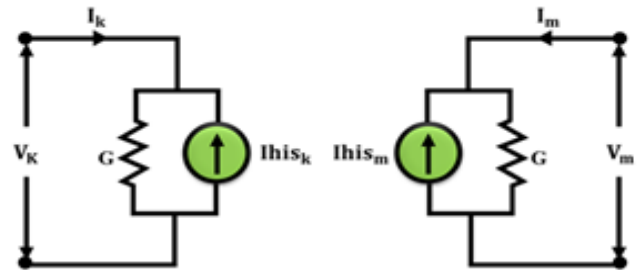


Figure 2: Process of FDLM

Figure 2 illustrates the FDLM process, which simulates fast and very fast transients through GIS and cables. It precisely models high-voltage cable behavior, predicting surge reflections and avoiding insulation failure. FDLM aids in defining BIL, selecting surge Arresters, and evaluating GIS insulation under various transient stress conditions.

3.1.4 Insulating Coordination Evaluation

Insulation coordination is the process of selecting and evaluating the electrical insulation strength of equipment in relation to the expected over voltages in a power system. The first step in insulation coordination is identifying the various types of over voltages that can occur in the system. over-voltage generally fall into three categories: lightning over voltages, which are caused by direct lightning strikes or nearby strikes; switching over voltages, which occur when switching operations such as opening or closing circuit breakers create voltage spikes.

4. Results and Discussion

In this paper, PSCAD™/EMTDC® V5.0.2 is a tool used for which stands for Power System Computer Aided Design / Electromagnetic Transients, is a dynamically typed language renowned for its implementation technique.

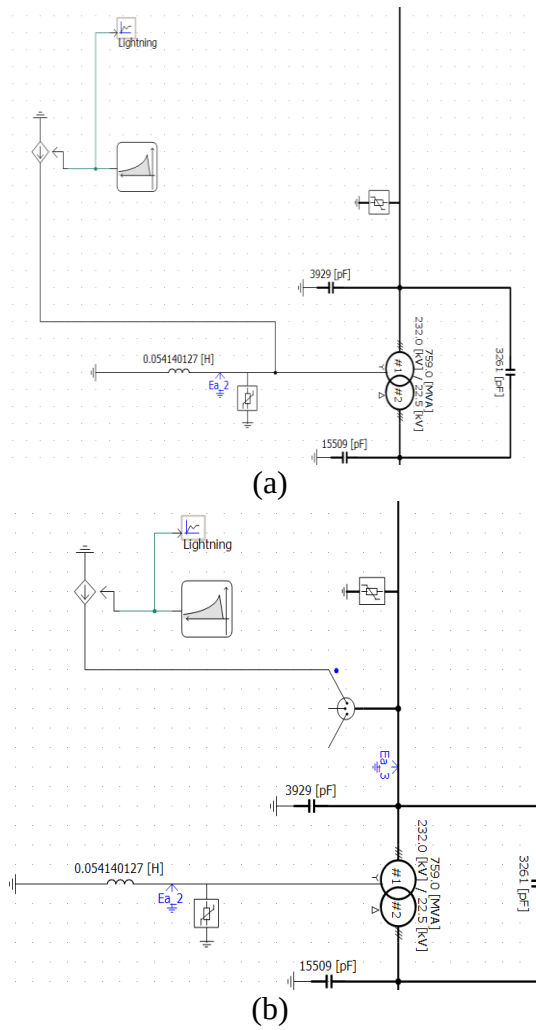


Figure 3: Simulation diagram of direct lightning at transformer 3 (a) Neutral and 3 (b) Bushing

Table 1: FFO Study Results at transformer neutral

Case	Lightning Impulse Withstand level (kV _{peak})	Maximum peak Overvoltage at transformer bushing (kV)	Protective margin (Insulation level/ Max peak overvoltage ≥ 1.2)	Surge Arrester Energy Absorption (kJ)	Energy Dissipation Capability of Surge Arrester (kJ)
1	325	188.73	1.72	72.194	576
2	325	204.11	1.59	87.753	576

Table 2: FFO Study Results at transformer bushing

Case	Lightning Impulse Withstand level (kV _{peak})	Maximum peak Overvoltage at transformer bushing (kV)	Protective margin (Insulation level/ Max peak overvoltage ≥ 1.2)	Surge Arrester Energy Absorption (kJ)	Energy Dissipation Capability of Surge Arrester (kJ)
3	1050	529.463	1.98	10.713	2400
4	1050	603.442	1.74	20.368	2400

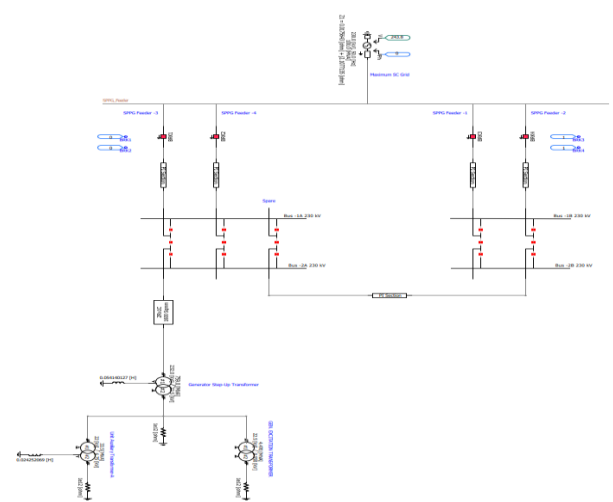


Figure 4: Simulation of Fast Front over Voltage / Lightning Impulse Over-voltage PSCAD File

Case 1: 20kA (8/20 μ s) Direct lightning at Transformer Neutral with Surge Arresters

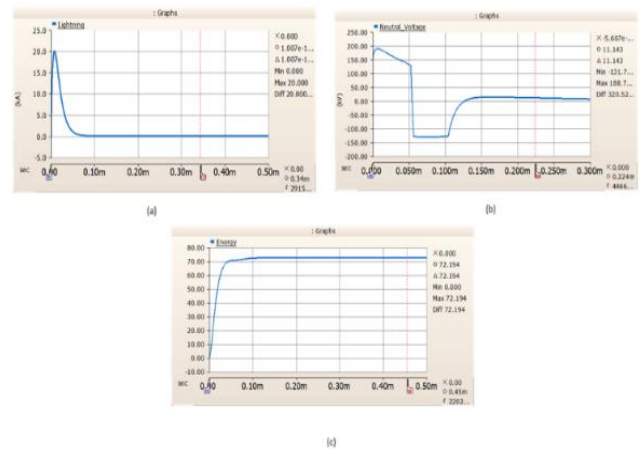


Figure 5: (a) Lightning Current, (b) Neutral Voltage and (c) Surge Arresters Energy

Table 3: Case 1 - FFO Study Results at transformer neutral

Case	Lightning Impulse Withstand level (kV _{peak})	Maximum peak Overvoltage at transformer bushing (kV)	Protective margin (Insulation level/ Max peak overvoltage ≥ 1.2)	Surge Arrester Energy Absorption (kJ)	Energy Dissipation Capability of Surge Arrester (kJ)
1	325	188.73	1.72	72.194	576

Case 2: 20kA (1.5/20 μ s) Direct lightning at Transformer Neutral with Surge Arresters

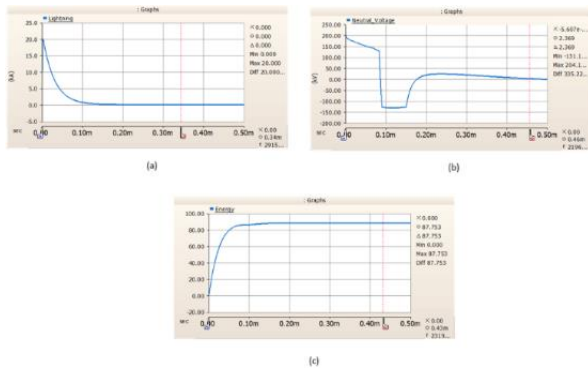


Figure 6: (a) Lightning Current, (b) Neutral Voltage and (c) Surge Arresters Energy

Table 4: Case 2 - FFO Study Results at transformer neutral

Case	Lightning Impulse Withstand level (kV _{peak})	Maximum peak Overvoltage at transformer bushing (kV)	Protective margin (Insulation level/ Max peak overvoltage ≥ 1.2)	Surge Arrester Energy Absorption (kJ)	Energy Dissipation Capability of Surge Arrester (kJ)
2	325	204.11	1.59	87.753	576

Case 3: 20kA (8/20 μ s) Direct lightning at Transformer bushing with Surge Arresters

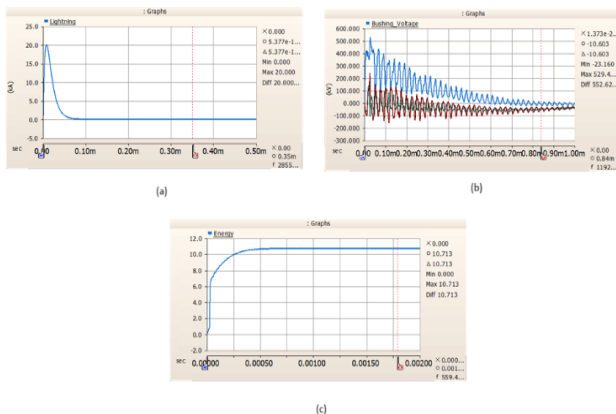


Figure 7: (a) Lightning Current, (b) Voltage peak at transformer HV Side and (c) Surge Arresters Energy

Table 5: Case 3 - FFO Study Results at transformer bushing

Case	Lightning Impulse Withstand level (kV _{peak})	Maximum peak Overvoltage at transformer bushing (kV)	Protective margin (Insulation level/ Max peak overvoltage ≥ 1.2)	Surge Arrester Energy Absorption (kJ)	Energy Dissipation Capability of Surge Arrester (kJ)
3	1050	529.463	1.98	10.713	2400

Case 4: 20kA (1.5/20 μ s) Direct lightning at Transformer bushing with Surge Arresters

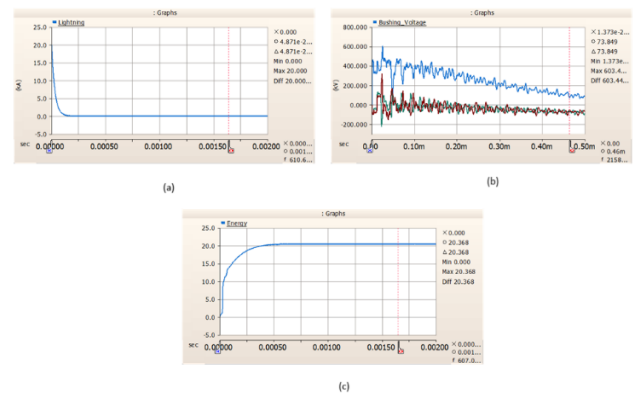


Figure 8: (a) Lightning Current, (b) Voltage peak at transformer HV Side and (c) Surge Arresters Energy

Table 6: Case 4 - FFO Study Results at transformer bushing

Case	Lightning Impulse Withstand level (kV _{peak})	Maximum peak Overvoltage at transformer bushing (kV)	Protective margin (Insulation level/ Max peak overvoltage ≥ 1.2)	Surge Arrester Energy Absorption (kJ)	Energy Dissipation Capability of Surge Arrester (kJ)
4	1050	603.442	1.74	20.368	2400

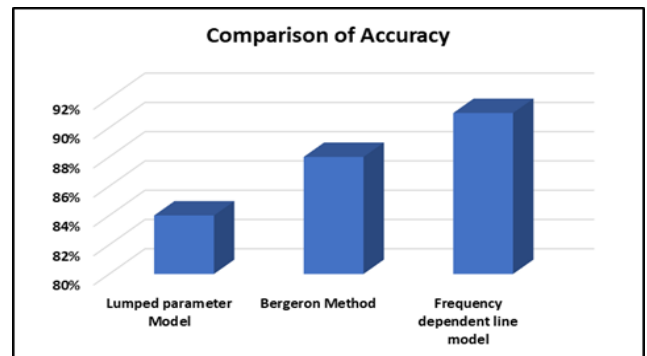


Figure 9: Comparison of Accuracy

Figure 9 shows the comparison of accuracy with different techniques such as Lumped parameter model [16], Bergeron method [17] and FDLM with the highest accuracy of 91%.

5. Conclusion

This research focuses on insulation coordination in a 230 kV GIS using advanced power system simulation tools. Unlike traditional Medium Voltage (MV) systems that rely on conservative insulation designs with large safety margins, High Voltage GIS installations demand precise evaluation of insulation performance under various transient conditions. Lightning and

switching surges significantly influence GIS insulation integrity. Through detailed simulations, the study evaluates over-voltage events to optimize insulation levels and strategically place protective devices. A key component in this strategy is the use of MOSA, which provide rapid response and high energy absorption during transient events. Unlike older spark gap-based Arresters, MOSAs, composed mainly of zinc oxide (ZnO), offer superior protection due to their nonlinear voltage-current characteristics and self-restoring capability.

References

1. C. V. K. Bhanu, "Optimizing Performance and over-voltage Resilience in 765 Kv Gas Insulated Substations: A Multi-Faceted Insulation Coordination Analysis".
2. Busyairi Samad; Salama Manjang; Ikhlas Kitta; Dianti Utamidewi; Arham Amri, Year: 2024, "Insulation Coordination System 150kV Substation and Transmission Line against Lightning Surge Interference in a Nickel Smelting Plant", *Journal of Applied Data Sciences* 5, No: 2 pp. 712-723.
3. Mansoor Soomro; Riaz Abbasi; Mazhar Baloch; Sohaib Tahir Chauhdary; Mokhi Maan Siddiqui, Year: 2024, "Assessment of Insulation Coordination and over-voltage for Utility Grids Integrated with Solar Farms", *Energies* 17, No: 21, pp. 5487.
4. Ronny Mustajärvi, Year: 2024, "Standard design criteria for electrical substations".
5. Hemant Kumar, Year: 2023, "Practical Training Report on Operation & Maintenance (Under 11kv)", Phd Diss., Srm University, Delhi.
6. Ahmad Talaat Hifzy, Year: 2023, "The Paradigm Shift for Substations Technology within Wind Power Applications from Onshore to Floating".
7. T. Hamel; S. Bedoui; A. Bayadi, Year: 2025, "Impact of transmission line lightning performance on an operational substation reliability considering the lightning stroke incidence angle", *Electrical Engineering & Electromechanics* 1, pp. 56-64.
8. Tiago Antunes; A. Rui Castro; Paulo J. Santos; Armando J. Pires, Year: 2023, "Standardization of Power-from-Shore Grid Connections for Offshore Oil & Gas Production", *Sustainability* 15, No: 6, pp. 5041.
9. Nambi Shankar; P. E. Balakrishnan Mani; John K. John, Year: 2022, "Optimizing Transformer Specification Based On Application and Rating", In 2022 IEEE IAS Petroleum and Chemical Industry Technical Conference (PCIC), pp. 107-114.
10. Shuhang Shen; Bin Cao; Peter Crossley; Zhongdong Wang; Xiaolin Ding, Year: 2022, "Transformation of a three-phase double-circuit overhead transmission line into a six-phase feeder to increase power transfer capability", *IET Generation, Transmission & Distribution* 16, No: 23, pp. 4663-4671.
11. Faridoddin Safaei; Mohsen Niasati, Year: 2024, "A new method for surge Arresters placement in high-voltage substations considering environmental effects", *IET Science, Measurement & Technology* 18, No: 9, pp. 550-563.
12. Haliloglu; Ali Burhan; Ires Iskender, Year: 2023, "Surge Arresters allocation for lightning protection of VSC based HVDC prototype", *Engineering Science and Technology, an International Journal* 48, pp. 101565.
13. Tobiloba Kollawole Adenekan, Year: 2024, "Understanding Surge Arresters through Frequency and Time Series Analysis in Power Distribution Networks".
14. Dantian Zhong; Lei Gao; Zhiyuan Cai, Year: 2024, "Design of Defect Identification and Location System for UHV AC Surge Arresters (April 2024)", *IEEE Access*.
15. Mohammadamin Moghbeli; Shahab Mehraeen; Sudipta Sen, Year: 2024, "Application of Surge

Arresters in Limiting Voltage Stress at Direct Current Breaker”, Applied Sciences 14, No: 18, pp. 8319.

16. Hanchi Zhang; Hongyang Zhou; Filipe Faria da Silva; Claus Leth Bak, Year: 2025, “Feasibility analysis and design of a novel gas-electricity integrated transmission system”, CSEE Journal of Power and Energy Systems.

17. Christian M. Franck; Michael Walter; Sergo Sagareli; Karsten Juhre, Year: 2024, “Electric Performance of New Non-SF₆ Gases and Gas Mixtures for Gas-Insulated Systems”, IEEE Electrical Insulation Magazine 40, No: 2, pp. 5-13.