[1]Manisha Tyagi

M. Ishrat Khan[2]

Sandeep Gupta[3]

A Comprehensive Study of Voltage Swell and Sag in Power Distribution Systems: Characteristics, Causes, Effects, and Mitigation Strategies

Journal of Electrical Systems

Abstract: - Voltage variations, such as swells and sags, are prevalent disturbances in power distribution systems, posing significant challenges to system reliability and equipment performance. This research paper provides a comprehensive study of voltage swell and sag phenomena, encompassing their characteristics, causes, effects, mitigation strategies, and case studies. The study explores the magnitude, duration, and frequency of voltage variations, delving into the underlying factors contributing to their occurrence, including switching operations, faults, and load variations. Moreover, the paper examines the detrimental effects of voltage variations on electrical equipment and industrial processes, highlighting the importance of understanding and mitigating these disturbances. Various mitigation techniques, such as voltage regulation, uninterruptible power supplies (UPS), and dynamic voltage restorers (DVRs), are evaluated for their effectiveness in minimizing the impact of voltage variations. Additionally, the paper explores the use of PWM-based Distribution Static Synchronous Compensator (DSTATCOM) as a promising solution for mitigating voltage swell and sag issues, discussing principles, design considerations, control strategies, and performance evaluation. Through case studies, simulation results, and modeling approaches using MATLAB/Simulink, the research paper offers valuable insights into the complex landscape of voltage swell and sag in power distribution systems, equipping researchers and practitioners with knowledge to address these challenges effectively.

Keywords: Voltage Swell; Voltage Sag; Power Distribution Systems; Mitigation Strategies; DSTATCOM.

1. Introduction

In power distribution systems, maintaining voltage stability is crucial for ensuring uninterrupted and reliable electricity supply to consumers (Gouws, 2015). Voltage stability refers to the ability of the system to maintain voltage levels within acceptable limits, preventing disruptions in electrical equipment operation and safeguarding against potential damage (Joshi et al., 2019). It plays a pivotal role in sustaining the efficiency and safety of power distribution systems, as consistent voltage levels are essential for the optimal performance of electrical equipment, ranging from sensitive electronic devices to heavy machinery used in industrial processes (Bajaj et al., 2020). Fluctuations in voltage can lead to equipment malfunctions, premature wear and tear, and even catastrophic failures, endangering both personnel and property (Li et al., 2016). Moreover, voltage stability ensures the quality of electrical supply, which is indispensable for various sectors, including manufacturing, healthcare, telecommunications, and residential utilities (Alkahtani et al., 2020).

Voltage swell and sag represent significant challenges to voltage stability in power distribution systems (Network, 2023). Swells manifest as short-term increases in voltage magnitude, often lasting for a few cycles, and can result from events such as capacitor switching or load disconnection (Kulkarni & Virulkar, 2023). Conversely, voltage sags entail temporary reductions in voltage magnitude, typically caused by faults, motor starting, or sudden changes in load demand (Khaleel et al., 2023). Understanding the characteristics and causes of these phenomena is crucial for identifying their root causes and implementing effective mitigation strategies (Khelef et al., 2010). Voltage variations, particularly swells and sags, can have detrimental effects on electrical equipment and industrial processes, leading to equipment malfunctions, production downtimes, and potential safety hazards (Alkahtani et al., 2020). Therefore, comprehensive knowledge of voltage swell and sag phenomena is essential for maintaining the reliability and stability of power distribution networks (Douglas, 2005).

The objectives of this research paper encompass investigating the characteristics and underlying causes of voltage swell and sag events, evaluating their effects on electrical equipment and industrial processes, exploring various mitigation techniques to minimize their impact, presenting case studies and simulation results to illustrate their

[1]Research Scholar, Department of Electrical & Electronics Engineering, Dr. K. N. Modi University, Newai, Rajasthan (India), manisha.kngd@gmail.com

[2]Department of Electrical & Electronics Engineering, Dr. K. N. Modi University, Newai, Rajasthan (India), isharatkhan.indore@gmail.com

[3]Department of Electrical Engineering, Graphic Era University (Deemed to be University), Dehradun, Uttarakhand (India), jecsandeep@gmail.com

effects on power distribution systems, and discussing emerging technologies such as PWM-based DSTATCOM for mitigating voltage variations. Through these objectives, the paper aims to contribute to the existing body of knowledge on voltage stability and provide valuable insights for researchers, practitioners, and stakeholders in the field. The subsequent sections delve into the characteristics, causes, and effects of voltage swell and sag, exploring mitigation techniques such as voltage regulation, UPS systems, APFs, and DVRs. The research methodology section outlines the approach, including theoretical analysis and simulation using MATLAB/Simulink, followed by case studies and simulation results illustrating the impact of voltage variations and the efficacy of mitigation strategies. Finally, the paper discusses advancements in PWM-based DSTATCOM for mitigating voltage variations, focusing on principles, design considerations, control strategies, and performance evaluation, culminating in a conclusion emphasizing the importance of the study's findings for power quality management and the reliability of power distribution systems.

2. Characteristics of Voltage Swell and Sag

Voltage swell and sag are transient disturbances in power distribution systems characterized by temporary deviations from nominal voltage levels (Das et al., 2018). Swells refer to short-term increases in voltage magnitude, typically lasting for a few cycles, while sags entail temporary reductions in voltage magnitude (Srivastava et al., 2023). These phenomena can have significant impacts on electrical equipment and industrial processes, making it essential to understand their characteristics for effective mitigation.

Voltage variations are typically measured and quantified using parameters such as magnitude, duration, and frequency. The magnitude of a voltage swell or sag is the difference between the peak or trough voltage level and the nominal voltage level (Ravi et al., 2023). It is often expressed as a percentage of the nominal voltage level, providing a quantitative measure of the deviation. Mathematically, the magnitude (M) of a voltage variation can be calculated as:

$$M = \frac{V_{Peak} - V_{Nominal}}{V_{Nominal}} \times 100\ \% \qquad (1)$$

Where V_{Peak} is the peak voltage level during the event, and $V_{Nominal}$ is the nominal voltage level. The duration of a voltage variation refers to the time interval during which the voltage deviates from the nominal level. It is typically measured in milliseconds or cycles and provides insights into the temporal characteristics of the disturbance. The duration of a voltage swell or sag can vary depending on the underlying cause and system response. Frequency denotes how often voltage variations occur within a given time period. It is expressed in hertz (Hz) or cycles per second and reflects the recurrence rate of swell and sag events in the power distribution system. Frequency analysis helps in understanding the prevalence and temporal distribution of voltage variations.

In voltage swell and sag events, several typical characteristics are observed. Swells are characterized by rapid increases in voltage magnitude, often exceeding predefined thresholds for a short duration (Douglas, 2005). They may result from events such as capacitor switching or load disconnection, leading to transient overvoltages in the system. Conversely, sags involve temporary reductions in voltage magnitude below the nominal level, typically caused by faults, motor starting, or sudden changes in load demand (Das et al., 2018). Sags can vary in depth and duration depending on the severity of the underlying cause and system response. Additionally, voltage variations may exhibit asymmetrical waveforms, phase imbalances, and harmonic distortions, further complicating their characterization and analysis.

In summary, voltage swell and sag events are characterized by their magnitude, duration, and frequency, which are essential parameters for quantifying and understanding these disturbances in power distribution systems. By comprehensively analyzing these characteristics, researchers and practitioners can develop effective mitigation strategies to enhance the reliability and stability of electrical networks.

3. Causes of Voltage Swell and Sag

Voltage swell and sag in power distribution systems can result from a variety of factors, ranging from routine operations to unexpected faults. Understanding these factors is crucial for effective mitigation and management of voltage variations.

One common cause of voltage swell and sag is the switching of large loads or power sources within the distribution system (Srivastava et al., 2023). When large loads are energized or de-energized, rapid changes in current flow can lead to transient voltage variations. For example, switching on or off a motor or capacitor bank can result in voltage swells or sags due to the sudden increase or decrease in demand. In a manufacturing facility, the sudden startup of heavy machinery such as compressors or pumps can cause voltage sags, affecting other equipment connected to the same power source.

Electrical faults, such as short circuits or ground faults, are another significant cause of voltage variations in distribution systems (Ravi et al., 2023). These faults can disrupt the normal flow of electricity and result in sudden changes in voltage levels. Faults may occur due to equipment failures, insulation breakdown, or environmental factors such as lightning strikes. For instance, a short circuit in an underground cable network can cause a voltage sag, affecting nearby industrial facilities and residential areas connected to the same distribution network.

Inadequate reactive power compensation or improper operation of compensation devices can also contribute to voltage variations (Topologies & Converters, 2020). Reactive power is necessary for maintaining voltage levels in AC power systems, and deficiencies in reactive power compensation can lead to voltage fluctuations. A malfunctioning capacitor bank intended for power factor correction may inadvertently inject excessive reactive power into the system, causing voltage swells during light load conditions.

Rapid changes in load demand, such as motor starting or tripping, can also induce voltage fluctuations in distribution systems (Bingham, 1998). These variations occur due to the transient nature of load dynamics and the interaction between different loads connected to the same network. For example, the simultaneous startup of multiple air conditioning units in a commercial building can result in a voltage sag, impacting other equipment and causing temporary disruptions in power supply.

A case study in a residential area exemplifies the consequences of such voltage variations (Qashou et al., 2021). The sudden tripping of a large industrial load connected to the same feeder as residential homes led to a voltage swell, causing damage to electronic appliances and requiring repairs to the affected equipment. This underscores the importance of understanding and mitigating the various causes of voltage swell and sag in power distribution systems to ensure the reliability and stability of the electrical network.

4. Effects of Voltage Swell and Sag

Voltage swell and sag events can have significant detrimental effects on electrical equipment and industrial processes, leading to operational disruptions, equipment damage, and financial losses (Sedaghati et al., 2013). Understanding these effects is crucial for implementing effective mitigation strategies and maintaining the reliability of power distribution systems.

One of the primary effects of voltage variations is damage to sensitive electronic equipment (Hossain et al., 2018). Voltage swells and sags can cause overheating, insulation breakdown, and component damage in electronic devices such as computers, servers, and control systems. For example, a voltage swell exceeding the rated voltage of sensitive electronic equipment can result in permanent damage to integrated circuits and other components, rendering the equipment inoperable.

In industrial settings, voltage fluctuations can disrupt critical processes and production operations (Hernández-Mayoral et al., 2023). Voltage sags, in particular, can lead to equipment tripping, production downtime, and loss of revenue for manufacturing facilities. For instance, a voltage sag occurring during the operation of industrial machinery can cause motors to stall, interrupting production lines and delaying product delivery to customers.

Furthermore, frequent exposure to voltage variations can reduce the lifespan of electrical equipment, leading to increased maintenance costs and downtime (Veizaga et al., 2023). Continuous operation under non-standard voltage conditions can accelerate wear and tear on equipment components, resulting in premature failure and the need for frequent repairs or replacements. For example, voltage sags caused by grid disturbances can subject motors and other rotating equipment to mechanical stresses, reducing their operational life expectancy.

Real-world examples and case studies provide insights into the impacts of voltage swell and sag events on power distribution systems and industrial operations. For instance, a case study conducted in a semiconductor manufacturing facility documented the effects of voltage swells on production equipment (Moshtagh et al., 2009).

The study found that voltage swells caused by grid disturbances resulted in equipment downtime, product defects, and financial losses for the facility.

Similarly, a case study in a commercial building demonstrated the consequences of voltage sags on sensitive electronic equipment (Soomro et al., 2021). Voltage sags occurring during peak load periods caused computers and other electronic devices to malfunction, leading to data loss and operational disruptions for tenants and businesses.

Overall, the effects of voltage swell and sag events underscore the importance of implementing effective mitigation strategies and maintaining voltage stability in power distribution systems. By minimizing voltage variations and ensuring the reliability of electrical equipment, utilities and industrial operators can reduce the risk of operational disruptions and financial losses associated with voltage fluctuations.

5. Mitigation Techniques

Mitigation techniques are essential in minimizing the impact of voltage variations, such as swells and sags, on power distribution systems. These techniques aim to stabilize voltage levels, improve power quality, and safeguard electrical equipment and industrial processes from disruptions. Several mitigation strategies are commonly employed, including voltage regulation, uninterruptible power supplies (UPS) systems, active power filters, and dynamic voltage restorers (DVRs).

Voltage Regulation

Voltage regulation plays a crucial role in stabilizing voltage levels within acceptable limits in power distribution systems. Voltage regulators and static var compensators (SVCs) are commonly used devices for this purpose (Caicedo et al., 2023). By injecting or absorbing reactive power into the system, these devices compensate for fluctuations in load demand or grid conditions, thereby maintaining voltage stability. Voltage regulation offers continuous control over voltage levels, making it an effective strategy for mitigating voltage variations before they impact downstream equipment. However, the installation and maintenance costs associated with voltage regulation devices can be significant, and their effectiveness may be limited in mitigating voltage variations caused by external factors such as grid disturbances or faults.

Uninterruptible Power Supplies (UPS) systems

UPS systems provide critical backup power during voltage disturbances, ensuring uninterrupted operation of sensitive equipment (Xu et al., 2016). These systems utilize energy storage devices such as batteries or flywheels to supply power to loads during transient voltage events, such as sags or outages. UPS systems offer immediate protection against voltage variations, providing seamless power supply to critical equipment during disturbances. Despite their reliability, UPS systems require regular maintenance and testing to ensure optimal performance, and their energy storage capacity may be limited, constraining their ability to sustain prolonged power outages.

Active Power Filters (APFs)

APFs mitigate voltage variations by compensating for harmonic distortions and reactive power fluctuations in the power distribution network (Prasad et al., 2017). These devices use power electronics converters to inject corrective currents into the system, canceling out harmonic currents and stabilizing voltage levels. APFs offer precise control over power quality parameters, enhancing system reliability and efficiency. However, they may require sophisticated control algorithms and monitoring systems to optimize performance and coordination with other power system devices, and they consume additional energy to compensate for reactive power, leading to increased operating costs and energy losses.

Dynamic Voltage Restorers (DVRs)

Dynamic Voltage Restorers (DVRs) are specialized devices designed to inject compensating voltage during sag events, restoring voltage levels at critical loads (Gouws, 2015). These systems use energy storage devices and power electronics converters to inject voltage pulses into the system, compensating for voltage sags and minimizing disruptions to sensitive equipment. DVRs provide rapid response to voltage sags, restoring voltage levels within milliseconds and ensuring uninterrupted operation for critical loads. However, DVRs require careful sizing and configuration, and they are typically more expensive than other mitigation techniques, requiring significant upfront investment for deployment and maintenance.

6. Research Methodology

The research methodology employed in this comprehensive study of voltage swell and sag in power distribution systems encompasses both theoretical analysis and simulation using MATLAB/Simulink. The methodology is structured into several key steps to ensure a systematic investigation of the phenomena and their mitigation strategies:

Model Development

Simulation models were developed using MATLAB/Simulink and SimPowerSystems to accurately replicate voltage swell and sag events in power distribution systems. These models were designed to include representations of power sources, transmission lines, transformers, loads, and various mitigation devices.

Simulation Setup

The simulation parameters were carefully defined based on real-world data and industry standards. This included configuring the system voltage, power source frequency, transformer rating, load type and profile, fault types, and mitigation devices. These parameters provided the foundation for conducting meaningful simulations that mimic actual power distribution scenarios. Table 1 provides an overview of the simulation parameters used in the study.

Table 1 Simulation Parameters

Parameter	Value
System Voltage	11 kV
Power Source Frequency	50 Hz
Transformer Rating	1 MVA
Load Type	Resistive
Load Profile	Industrial
Fault Types	Line-to-line, Line-to-ground, Three-phase, Multistage
Mitigation Devices	Voltage Regulators (VSs), Static Var Compensators (SVCs), Dynamic Voltage Restorers (DVRs)

Simulation Scenarios

Various simulation scenarios were devised to explore the impact of voltage swell and sag under different operating conditions. These scenarios encompassed fault events, load variations, and the deployment of mitigation devices such as *VSs*, *SVCs*, and *DVRs*. Each scenario aimed to capture specific aspects of voltage variations and their effects on the power distribution system.

Data Collection and Analysis

Following the execution of simulations for each scenario, data collection and analysis were conducted meticulously. Key parameters such as voltage magnitude, duration of voltage variations, equipment response, and harmonic distortion were collected and analyzed. This rigorous analysis provided insights into the performance, reliability, and stability of power distribution system under varying conditions.

Calculation of Voltage Swell and Sag

The magnitude of voltage swell and sag events was calculated using appropriate equations. Voltage swell (V_s) was determined by subtracting the maximum voltage level during the event (V_{max}) from the nominal voltage level ($V_{nominal}$), expressed as:

$$V_s = V_{max} - V_{nominal} \quad (2)$$

Similarly, voltage sag (V_g) was calculated by subtracting the minimum voltage level during the event (V_{min}) from the nominal voltage level ($V_{nominal}$), as follows:

$$V_g = V_{nominal} - V_{min} \tag{3}$$

Total Harmonic Distortion (THD) Calculation

THD, which quantifies the distortion level of voltage waveform, was computed using established equations. The THD calculation involved analyzing the amplitude of harmonic components relative to the fundamental voltage component. It can be expressed as:

$$THD = \sqrt{\frac{\sum_{i=2}^{n} V_i^2}{V_i^2}} \times 100\ \% \tag{4}$$

where *THD* is the total harmonic distortion, V_i represents amplitude of each harmonic component, and V_1 is amplitude of fundamental voltage component.

Through this comprehensive research methodology, a detailed understanding of voltage swell and sag phenomena, their causes, effects, and mitigation strategies was attained. The integration of theoretical analysis with simulation-based investigation facilitated the exploration of system behavior and the evaluation of mitigation techniques, contributing to advancements in power distribution system reliability and stability.

7. Case Studies and Simulation Results

Several case studies and simulation results are presented to illustrate the impact of voltage swells and sags on power distribution systems and the effectiveness of mitigation techniques. These include real-world examples of voltage disturbance events, their causes, and the implemented mitigation strategies. Simulation results demonstrate the performance of various mitigation techniques in reducing voltage variations and ensuring system reliability.

7.1 Modeling approach

MATLAB/Simulink was utilized to construct the simulation models in conjunction with SimPowerSystems. Subsequently, it is employed to replicate diverse power quality disruptions and scrutinize the ways in which these perturbations warp the sinusoidal waveform of power system. To preserve their simplicity and reproducibility for the reader, the models were created with the fewest feasible blocks and always use their default values. The generated models in this paper also function as the fundamental building blocks of a more complex power system. Moreover, the Malaysian grid code serves as the basis for the models' distribution voltage level.

7.1.1 Line fault model

Simulink was used to generate the line fault model that is seen in Figure 1. The voltage drop that occurs as a result of electrical line problems is simulated by this model. An 11 kV/0.4 kV, 1 MVA delta/wye transformer is used to supply power to a 10-kW resistive and 100VAR inductive load. This transformer is supplied by an 11 kV/0.4 kV, 1 MVA delta/wye block that is connected to a 50 Hz three-phase source block. Measurement scopes for the instantaneous waveform and the root mean square (RMS) are installed at the 11 kV and 0.4 kV buses. The 11 kV bus is equipped with two fault blocks, which are positioned there in order to mimic both a line fault and a multistage breakdown. Using the ode23tb solver, the simulation is executed for a duration of 0.4 seconds.

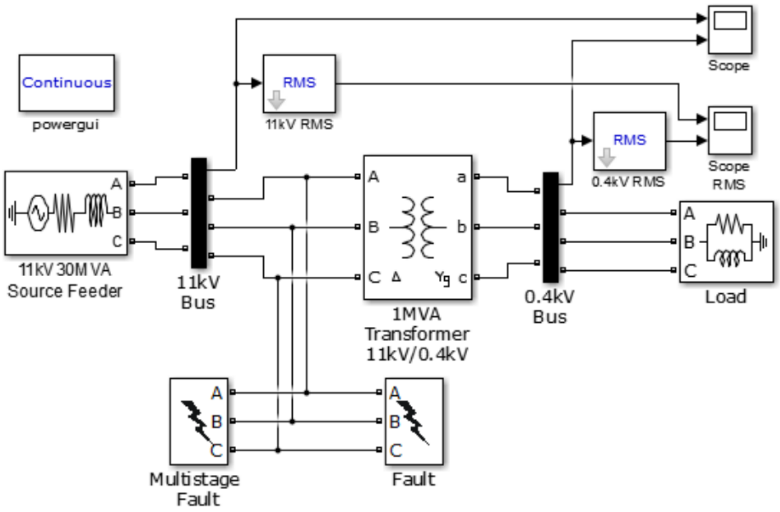

Figure 1 Simulink Model employed to introduce line faults

There are many different types of faults that may be simulated using this line fault model. Some of these faults include single line-to-ground, double line-to-ground, line-to-line, three-phase, and multistage faults. The voltage sag waveforms that are induced by a line-to-line fault between phases A and B on 11 kV feeder lines are depicted in Figure 2. These waveforms range from 0.1 to 0.168 seconds. Due to the presence of a high fault resistance of 8 Ω between the failed lines, the 11 kV bus experiences two voltage sags in phases A and B, each of which is associated with a distinct magnitude. According to Joshi et al.'s 2019 research, the voltage sag travels downstream through the 11 kV/0.4 kV, 1 MVA transformer until it reaches the load. The delta/wye transformer arrangement is responsible for changing the fault configuration. Because there is no ground point in the line-to-line fault and the fault resistance is considerable, the unfaulted phase C at the 0.4 kV bus sees a little voltage swell. This is because of the combination of these two factors. Research on power quality often involves the presentation of the magnitude of the voltage sag waveform in the form of a root-mean-square (RMS) waveform, which is then normalized for improved viewing. The RMS analysis of the line-to-line fault voltage sag waveforms that were shown in Figure 2 is depicted in Figure 3, which provides a clear visual representation of the sag magnitudes for each phase. Because of the phase shift that takes place during the fault, there are slight oscillations that take place throughout the pre- and post-sag and swell phases.

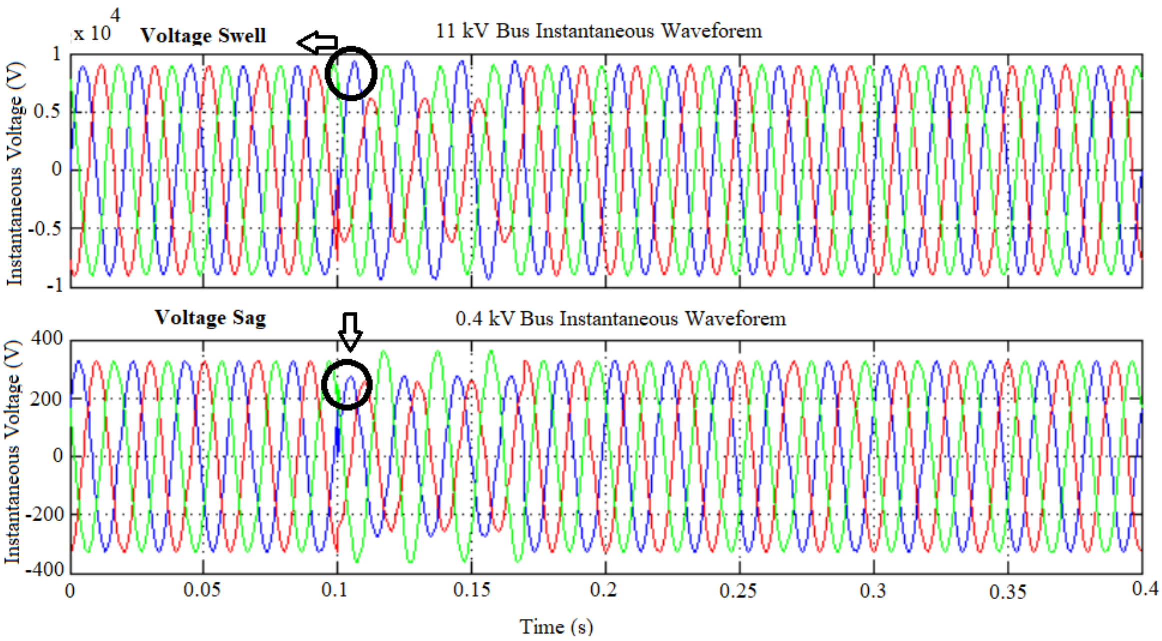

Figure 2 Instantaneous Voltages of 11kV and 0.4kV Waveforms showing Voltage Sag and Swell

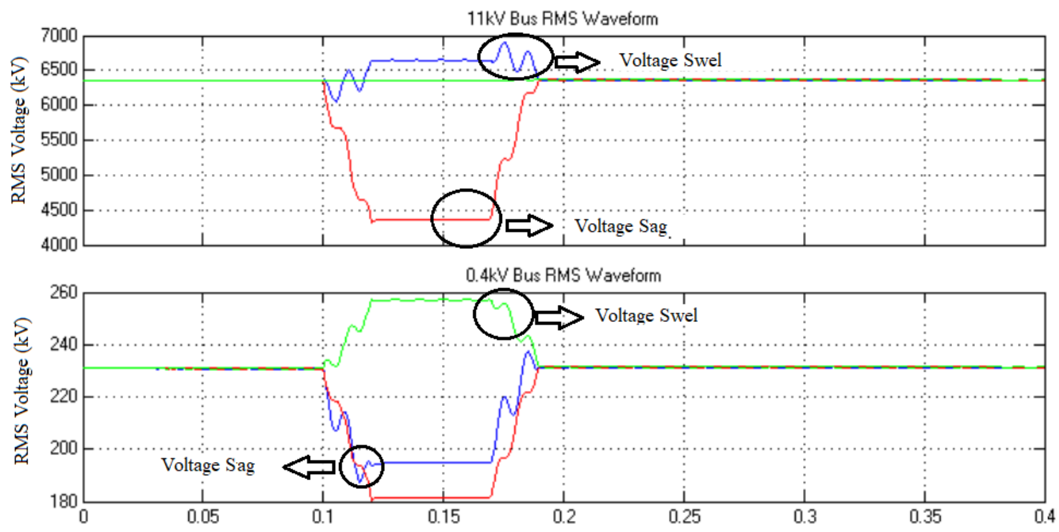

Figure 3 RMS Voltages of 11kV and 0.4kV Waveforms showing Voltage Sag and Swel

The line fault model can also simulate multistage line faults. Multistage voltage sags typically occur due to changes in fault or ground impedance during a fault, or because multiple protection relay clearing mechanisms are not synchronized. These factors alter the power system impedance and network configuration, causing the voltage sag to occur in stages before fully recovering to its nominal level (Bajaj et al., 2020). Multistage faults can also refer to several errors happening in quick succession, recorded as a single event. Figure 4 shows the instantaneous waveforms of a multistage voltage sag resulting from a double line-to-ground fault.

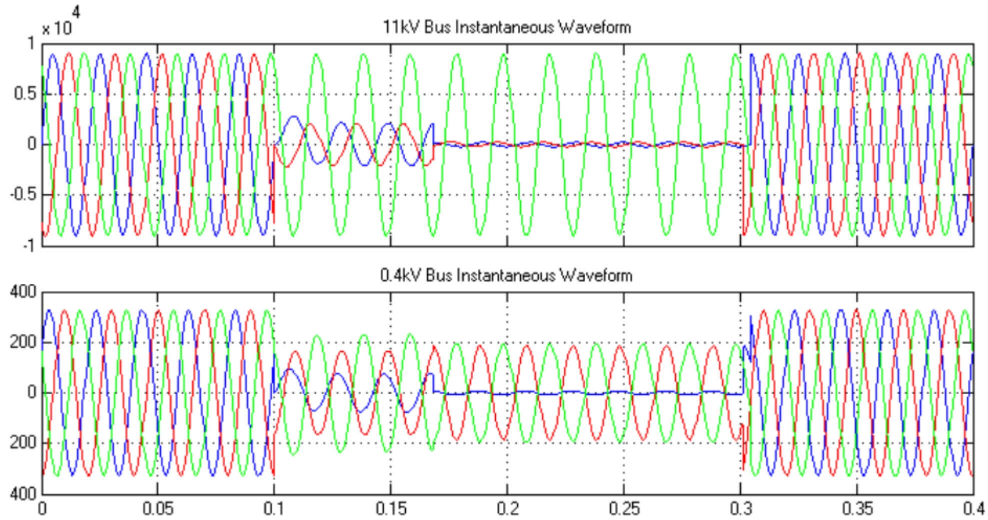

Figure 4 Instantaneous Voltages of 11kV and 0.4kV Waveforms for multi-stage faults showing multistage voltage sag

Figure 5 shows the RMS voltages of 11kV and 0.4kV waveforms during multi-stage faults, offering a visualization of the progression of voltage sag events. This representation allows observers to distinguish how voltage sags unfold in distinct stages, impacting both high-voltage (11kV) and low-voltage (0.4kV) buses.

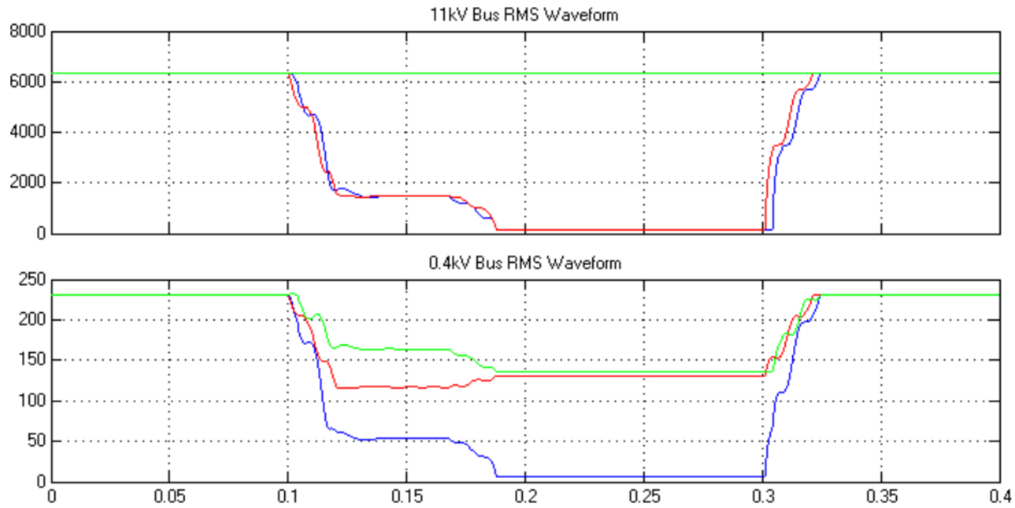

Figure 5 RMS Voltages of 11kV and 0.4kV Waveforms for multi-stage faults showing multistage voltage sag

7.1.2 Power Distribution Model for Induction motor/load Simulink

Figure 6 presents a detailed power distribution model specifically developed to simulate behavior of an induction motor/load setup. This model encompasses various components, including the induction motor itself, associated loads, protective devices like relays or circuit breakers, and connections to the power supply network. Through this model, we can analyze how voltage variations, such as swells and sags, impact the performance and operation of induction motor and connected load.

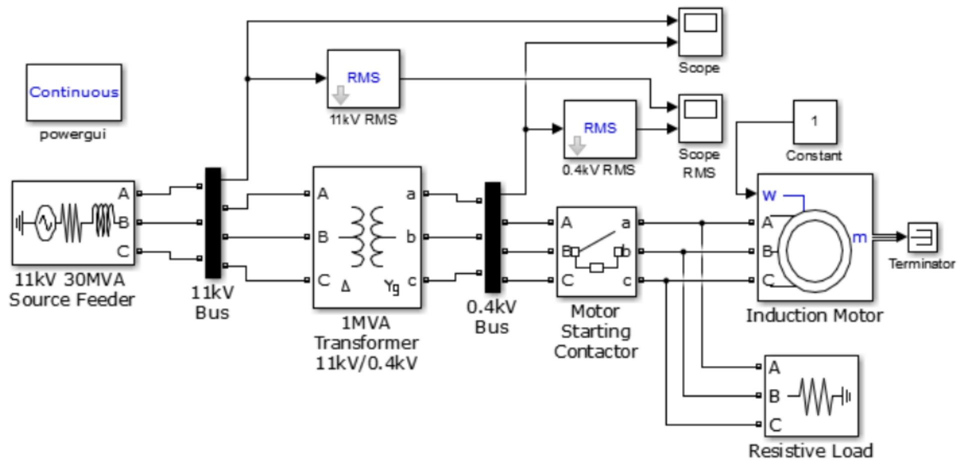

Figure 6 Power Distribution Model for Induction motor/load

Using the induction motor starting model, it is possible to simulate the voltage drop that occurs when a high-power industrial induction motor is started. The induction motor starting model that was constructed using Simulink is displayed in Figure 7. A three-phase induction motor, a resistive load of 10 kW, a three-phase breaker that functions as a motor starting contactor, a delta/wye transformer with 11 kV/0.4 kV and 1 MVA, and a three-phase source feeder block with 11 kV, 30 MVA, and 50 Hz are all components that are included in this model. For the purpose of taking measurements, instantaneous and root-mean-square waveform scopes have been positioned at the 0.4 kV and 11 kV busses. It takes 0.4 seconds for the simulation to complete, and it makes use of the ode23tb solver.

A three-phase voltage sag waveform is seen immediately after the motor starting contactor shuts after 0.1 seconds in Figure 7, which depicts an induction motor with a power output of 75 kW (100 horsepower). Through the utilization of a constant block, the starting speed of the induction motor is established at 1 rad/sec. After traveling through the transformer and upstream to the 11 kV feeder bus, the voltage drop that occurs at the 0.4 kV bus is transmitted. It is most noticeable in the waveforms of the 0.4 kV bus, and the magnitude of the voltage sag decreases as it advances upstream toward the 11 kV feeder. Figure 8 depicts the root-mean-square waveform for the induction motor load, which includes a voltage sag.

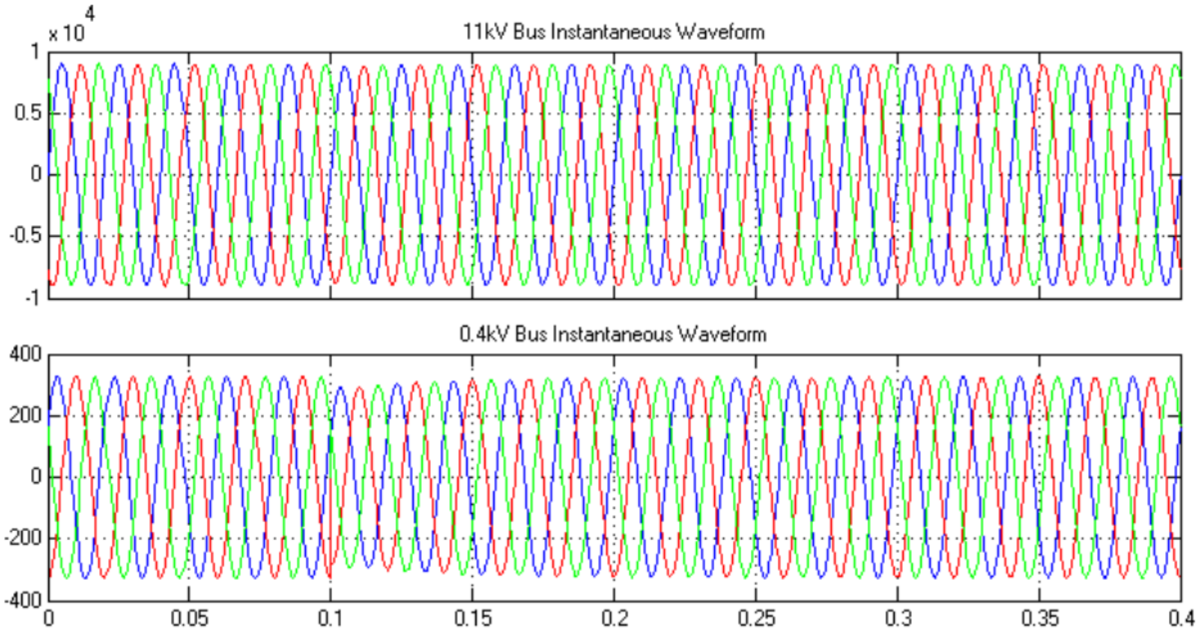

Figure 7 Instantaneous voltage waveform showing voltage sag for an induction motor load

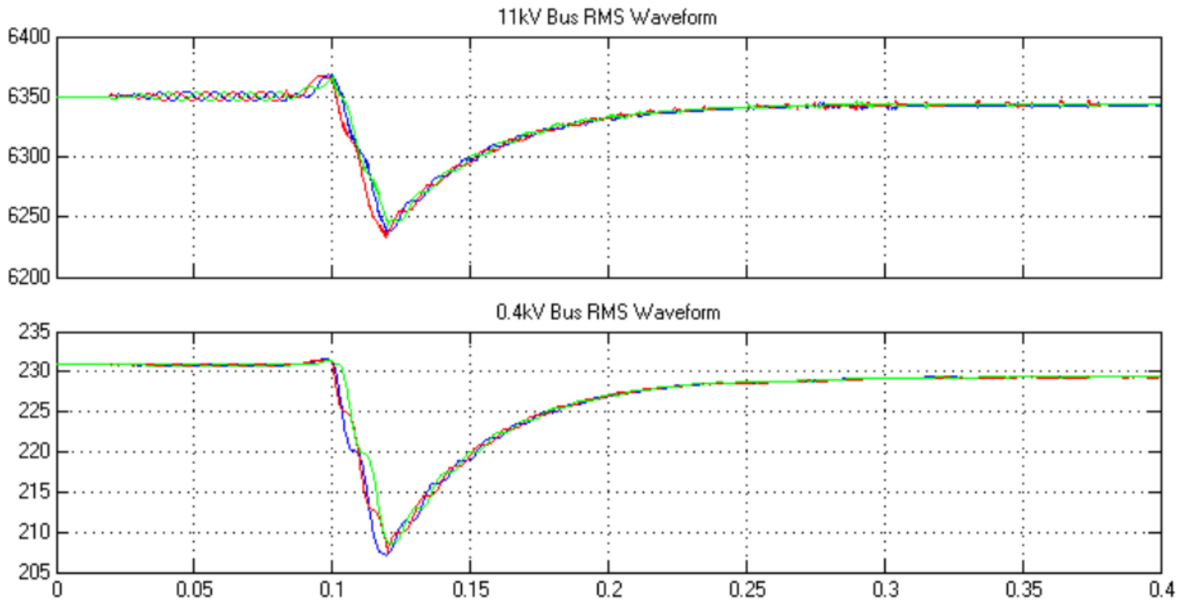

Figure 8 RMS voltage waveform showing voltage sag for an induction motor load

The voltage sag that is produced by an induction motor is characterized by three different characteristics: it is unbalanced, it has a shallow voltage sag that can fluctuate up to fifteen percent from its nominal magnitude, and it displays a high even harmonic of the second order.

In accordance with the IEC 61000-4-7 standard, the power GUI block is utilized to investigate the harmonic content. This block allows for the adjustment of frequencies up to 2,000 Hz and features a window that spans 10 cycles. This configuration makes it possible to conduct an analysis of harmonic content up to the forty-first order. In light of the fact that the voltage drop starts at 0.06 seconds, the waveform from 0.2 to 0.4 seconds is the primary focus of the investigation. According to Figure 9, the load voltage sag that occurs during Phase A of an induction motor is characterized by strong even harmonics of the second, sixth, twelveth, eighteenth, and twenty-fourth orders.

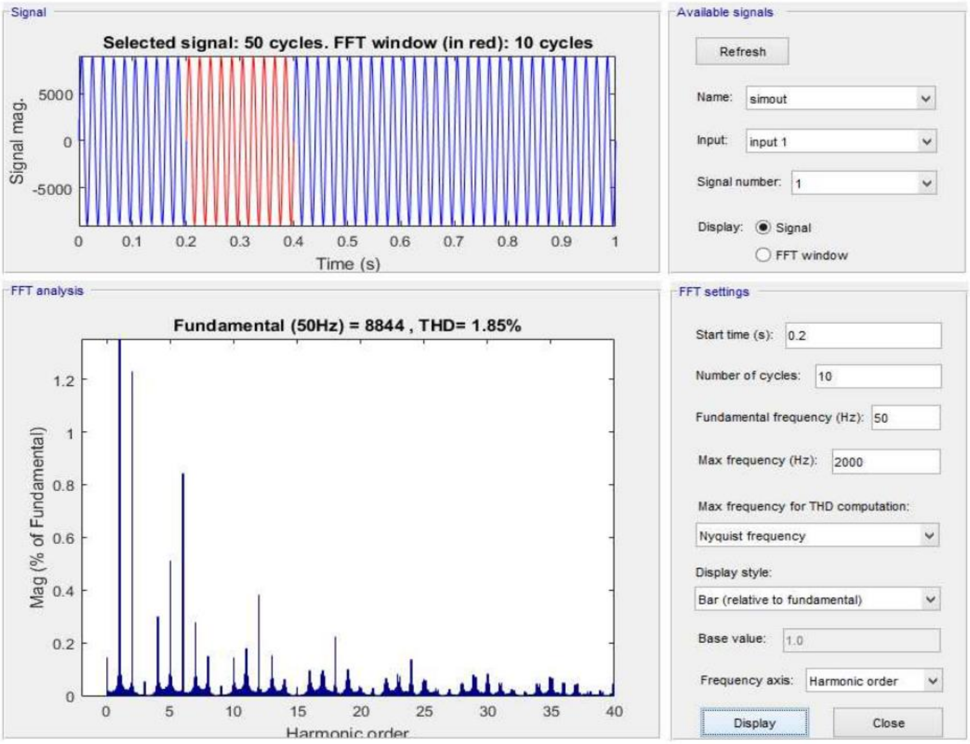

Figure 9 Total Harmonic Distortion (THD) analysis of phase a voltage sag caused by induction load at 11 kV bus

8. Mitigation of Voltage Swell and Sag issue using PWM – DSTATCOM:

In recent years, the rising demand for reliable and high-quality power supply has spurred research into advanced technologies to address voltage swell and sag issues in power distribution systems. PWM-based DSTATCOM has emerged as a promising solution, offering effective voltage regulation and improved power quality. This review examines the latest advancements in PWM-based DSTATCOM technology for mitigating voltage swell and sag issues, with a focus on the principles, design, control strategies, and performance evaluation of these systems.

8.1 Principles of PWM-Based DSTATCOM

PWM-based DSTATCOM operates by injecting compensating currents into the distribution system to mitigate voltage fluctuations, particularly swell and sag conditions. The compensating currents are generated using PWM techniques, which involve the rapid switching of power electronic devices such as insulated gate bipolar transistors (IGBTs) or power MOSFETs. By controlling the amplitude, phase, and frequency of the injected currents, PWM-based DSTATCOM can effectively regulate voltage at the point of common coupling (PCC) and improve power quality.

8.2 Design Considerations

The design of PWM-based DSTATCOM involves several key considerations to ensure optimal performance and reliability. These include the selection of power electronic devices, design of the voltage source converter (VSC), sizing of the energy storage system (ESS), and implementation of control algorithms. Various topologies, such as two-level, three-level, and multilevel inverters, have been proposed for PWM-based DSTATCOM, each offering unique advantages in terms of efficiency, cost, and complexity.

8.3 Control Strategies

PWM-based DSTATCOM must have effective control techniques in order to function properly and mitigate voltage swell and sag difficulties. This is vital for the successful operation of the device. In the process of voltage regulation, proportional-integral (PI) control is frequently utilized. This control method involves comparing the reference voltage to the voltage that is measured at the power conversion converter (PCC), and then utilizing the error signal to change the compensating currents. A number of sophisticated control approaches, including fuzzy logic control, neural network control, and model predictive control, have been researched in order to improve the dynamic performance and resilience of PWM-based DSTATCOM under a variety of different operating situations.

8.4 Performance Evaluation

The performance of PWM-based DSTATCOM is evaluated based on several metrics, including voltage regulation, harmonic distortion, transient response, and energy efficiency. Simulation studies using software tools such as MATLAB/Simulink and PSCAD/EMTDC provide insights into the behavior of PWM-based DSTATCOM under different load conditions and fault scenarios. Experimental validation on laboratory prototypes and field trials in real-world distribution systems further demonstrate the effectiveness and feasibility of PWM-based DSTATCOM in mitigating voltage swell and sag issues.

9. Conclusion

Voltage variations, specifically swell and sag events, pose substantial challenges to power distribution systems, impacting both reliability and equipment performance. This comprehensive study has delved into the intricacies of these phenomena, elucidating their characteristics, root causes, effects, and mitigation strategies. By meticulously examining the transient nature of voltage variations, characterized by deviations in magnitude, duration, and frequency, researchers and practitioners gain invaluable insights into quantifying and understanding these disturbances, laying the groundwork for effective mitigation measures.

Understanding the multifaceted causes of voltage swell and sag is paramount for devising targeted mitigation strategies. Factors such as load switching, electrical faults, reactive power compensation deficiencies, and load dynamics contribute to the occurrence of these disturbances. This study underscores the importance of identifying and addressing these root causes to implement measures aimed at minimizing the impact of voltage variations on power distribution systems.

The detrimental effects of voltage variations on electrical equipment and industrial processes have been thoroughly scrutinized in this study. From damage to sensitive electronic devices to disruptions in production operations, voltage swell and sag events can lead to significant financial losses and safety hazards. Mitigation techniques are indispensable for mitigating these effects and ensuring the reliability and stability of power distribution networks.

Evaluation of various mitigation techniques, including voltage regulation, UPS systems, APFs, and DVRs, has provided valuable insights into their effectiveness in stabilizing voltage levels and enhancing power quality. Notably, PWM-based DSTATCOM emerges as a promising solution, offering rapid response and precise control over voltage fluctuations. Through case studies and simulation results, this study has demonstrated the real-world impact of voltage variations on power distribution systems and validated the efficacy of mitigation techniques in reducing voltage disturbances.

In summary, this study makes a significant contribution to the field of power quality management by offering a comprehensive understanding of voltage swell and sag phenomena. By integrating theoretical analysis with simulation-based investigation, it equips researchers, practitioners, and stakeholders with practical insights and solutions for effectively addressing voltage variations in power distribution systems. Continued research and development efforts are essential to address evolving challenges and advance the state-of-the-art in power quality management, ensuring uninterrupted and high-quality power supply to consumers.

Disclosure statement

Authors have no potential conflict of interest to report concerning the research.

Funding

No funding is received to conduct the research work.

Data availability statement

The authors declare that data associated to outcomes of this study is available from corresponding author based on reasonable request.

References

1. Alkahtani, A. A., Alfalahi, S. T. Y., Athamneh, A. A., Al-Shetwi, A. Q., Mansor, M. Bin, Hannan, M. A., & Agelidis, V. G. (2020). Power Quality in Microgrids including Supraharmonics: Issues, Standards, and Mitigations. *IEEE Access*, *8*, 127104–127122. https://doi.org/10.1109/ACCESS.2020.3008042
2. Bajaj, M., Singh, A. K., Alowaidi, M., Sharma, N. K., Sharma, S. K., & Mishra, S. (2020). Power Quality Assessment of Distorted Distribution Networks Incorporating Renewable Distributed Generation Systems Based on the Analytic Hierarchy Process. *IEEE Access*, *8*, 145713–145737. https://doi.org/10.1109/ACCESS.2020.3014288
3. Bingham, R. P. (1998). *Sags and Swells*. *September 1994*, 13–14.
4. Caicedo, J. E., Agudelo-Martínez, D., Rivas-Trujillo, E., & Meyer, J. (2023). A systematic review of real-time detection and classification of power quality disturbances. *Protection and Control of Modern Power Systems*, *8*(1). https://doi.org/10.1186/s41601-023-00277-y
5. Das, C. K., Bass, O., Kothapalli, G., Mahmoud, T. S., & Habibi, D. (2018). Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality. *Renewable and Sustainable Energy Reviews*, *91*(March 2018), 1205–1230. https://doi.org/10.1016/j.rser.2018.03.068
6. Douglas, J. (2005). Electrical Power Quality. *Van Nostrand's Scientific Encyclopedia*. https://doi.org/10.1002/0471743984.vse2831
7. Gouws, R. (2015). Development of an axial suspended AMB experimental bench for load and disturbance tests. *Journal of Applied Research and Technology*, *13*(3), 382–391. https://doi.org/10.1016/j.jart.2015.07.004
8. Hernández-Mayoral, E., Madrigal-Martínez, M., Mina-Antonio, J. D., Iracheta-Cortez, R., Enríquez-Santiago, J. A., Rodríguez-Rivera, O., Martínez-Reyes, G., & Mendoza-Santos, E. (2023). A Comprehensive Review on Power-Quality Issues, Optimization Techniques, and Control Strategies of Microgrid Based on Renewable Energy Sources. *Sustainability (Switzerland)*, *15*(12). https://doi.org/10.3390/su15129847
9. Hossain, E., Tur, M. R., Padmanaban, S., Ay, S., & Khan, I. (2018). Analysis and Mitigation of Power Quality Issues in Distributed Generation Systems Using Custom Power Devices. *IEEE Access*, *6*(April), 16816–16833. https://doi.org/10.1109/ACCESS.2018.2814981
10. Joshi, I. M., Rai, A. S. D., & Pawar, R. (2019). *D-STATCOM based Distributed Generation Systems for Power Quality Improvement*. *6*(6), 74–80.
11. Khaleel, M., Yusupov, Z., Elmnifi, M., Elmenfy, T., & Rajab, Z. (2023). Assessing the Financial Impact and Mitigation Methods for Voltage Sag in Power Grid. *International Journal of Electrical Engineering and Sustainability (IJEES)*, *1*(2), 10–26.
12. Khelef, N., Mohamed, A., & Shareef, H. (2010). Practical mitigation of voltage sag in distribution networks by combining network reconfiguration and DSTATCOM. *PECon2010 - 2010 IEEE International Conference on Power and Energy*, *November*, 264–269. https://doi.org/10.1109/PECON.2010.5697588
13. Kulkarni, N. G., & Virulkar, V. B. (2023). Enhancing the Power Quality of Grid Connected Photovoltaic System during Fault Ride Through: A Comprehensive Overview. *Journal of The Institution of Engineers (India): Series B*, *104*(3), 821–836. https://doi.org/10.1007/s40031-023-00870-7
14. Li, R., Geng, H., & Yang, G. (2016). Fault ride-through of renewable energy conversion systems during voltage recovery. *Journal of Modern Power Systems and Clean Energy*, *4*(1), 28–39. https://doi.org/10.1007/s40565-015-0177-0
15. Moshtagh, J., Souraki, H. P., & Jalili, P. (2009). Characteristics analysis of voltage sag, voltage swell and instability voltage in multi-grounded four-wire power distribution systems. *2009 International Conference on Computer and Electrical Engineering, ICCEE 2009*, *2*(January 2009), 163–167. https://doi.org/10.1109/ICCEE.2009.157
16. Network, V. D. (2023). *Voltage Distribution Network*.
17. Prasad, M., Akella, A. K., Das, S., & Kumari, S. (2017). Voltage sag, swell and harmonics mitigation by solar photovoltaic fed ZSI based UPQC. *International Journal of Renewable Energy Research*, *7*(4), 1646–1655. https://doi.org/10.20508/ijrer.v7i4.6198.g7205

18. Qashou, A., Yousef, S., Smadi, A. A., & AlOmari, A. A. (2021). Distribution system power quality compensation using a HSeAPF based on SRF and SMC features. *International Journal of System Assurance Engineering and Management*, *12*(5), 976–989. https://doi.org/10.1007/s13198-021-01185-w
19. Ravi, T. R., Kumar, K. S., Dhanamjayulu, C., Khan, B., & Rajalakshmi, K. (2023). Analysis and mitigation of PQ disturbances in grid connected system using fuzzy logic based IUPQC. In *Scientific Reports* (Vol. 13, Issue 1). Nature Publishing Group UK. https://doi.org/10.1038/s41598-023-49042-z
20. Sedaghati, R., Afroozi, N. M., Nemati, Y., Rohani, A., Toorani, A. R., Javidtash, N., Heydarzadegan, A., & Sedaghati, H. (2013). A Survey of Voltage Sags and Voltage Swells Phenomena in Power Quality Problems. *Reza Sedaghati, IJSRM*, *1*(9), 2321–3418. www.ijsrm.in
21. Soomro, A. H., Larik, A. S., Mahar, M. A., Sahito, A. A., Soomro, A. M., & Kaloi, G. S. (2021). Dynamic Voltage Restorer—A comprehensive review. *Energy Reports*, *7*, 6786–6805. https://doi.org/10.1016/j.egyr.2021.09.004
22. Srivastava, A., Manas, M., & Dubey, R. K. (2023). Electric vehicle integration's impacts on power quality in distribution network and associated mitigation measures: a review. *Journal of Engineering and Applied Science*, *70*(1), 1–29. https://doi.org/10.1186/s44147-023-00193-w
23. Topologies, R., & Converters, P. (2020). Dynamic Voltage Restorer (DVR) A Comprehensive Review of Topologies, Power Converters, Control Methods, and Modified Configurations. *Energies*, *13*(16).
24. Veizaga, M., Delpha, C., Diallo, D., Bercu, S., & Bertin, L. (2023). Classification of voltage sags causes in industrial power networks using multivariate time-series. *IET Generation, Transmission and Distribution*, *17*(7), 1568–1584. https://doi.org/10.1049/gtd2.12765
25. Xu, Y., Xiao, X., Sun, Y., & Long, Y. (2016). Voltage sag compensation strategy for unified power quality conditioner with simultaneous reactive power injection. *Journal of Modern Power Systems and Clean Energy*, *4*(1), 113–122. https://doi.org/10.1007/s40565-016-0183-x