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Research Article

Assessing the Financial Impact and Mitigation Methods for Voltage Sag in Power Grid

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Abstract: Voltage sags, as defined by the IEEE Standard, refer to sudden drops in voltage magnitude that last for a duration greater than 0.5 cycles of the power frequency but less than or equal to 1 minute. These events are considered significant in power quality issues. The change rate of voltage during a voltage sag can range from 0.1 to 0.9 per unit (p.u.) of nominal voltage, where 1 p.u. represents the nominal voltage level. Addressing the power quality (PQ) challenge is a critical component of ensuring the reliable and efficient operation of modern power systems. Advances in PQ monitoring and control technologies, power electronic devices, smart grid technologies, and PQ standards have all contributed significantly to improving PQ and enhancing the resilience and responsiveness of power systems. However, voltage sags are particularly challenging to resolve and may require a range of solutions. Voltage sags are a critical factor in PQ and can cause significant disruptions in the power system. As a result, mitigating voltage sags is a key area of focus in PQ improvement efforts. This paper presents an in-depth analysis of voltage sags in power grid, including their causes, characteristics, and harmful effects on electrical equipment and industrial processes. The authors highlight the significance of voltage sag mitigation techniques to reduce the economic losses and damage caused by these PQ issues. The paper provides an overview of existing mitigation techniques, including dynamic voltage restorer (DVR), distribution static synchronous compensator (D-STATCOM), and other custom solutions. Additionally, the paper discusses the economic impact of voltage sag on various industrial sectors, including the semiconductor and information industries. The authors emphasize the need for continued research and development of effective voltage sag mitigation techniques to enhance the stability and reliability of power grid and electrical systems. This paper is a valuable resource for researchers, engineers, and professionals in the field of power systems, providing insights into the causes and mitigation of voltage sags in the power grid.

Keywords: Power Quality; Financial Impact; Voltage Sag Mitigation; D-FACTS; Power Grid

1. Introduction

The notion of power quality (PQ) pertains to the capacity of the electricity grid to provide its consumers with dependable, optimal, and non-permissive electricity [1]. The complexities of PQ issues can be segmented into various tiers. Initially, it solely pertained to the availability of electrical power, as well as the regulation of voltage and frequency within a particular range [2]. However, due to the heightened sensitivity of electrical equipment, the growing awareness of consumers, and the escalating prevalence of PQ disturbances within the system, PQ is currently receiving greater attention [3]. As such, the concept must now encompass additional facets such as harmonic distortion, short-term transients, imbalances, interruptions, and flickers, in addition to its initial requirements [4]. In this context, the existence of standards related to PQ from both IEEE and IEC, such as IEC 61000, En50160, and IEEE 519, underscores the importance of PQ issues in modern power systems. Although IEEE has standards addressing PQ, they are not as structured and comprehensive as their IEC counterparts [5-9].

The integration of power electronic devices into the modern power grid has enabled significant advancements in power system technology and functionality. However, these devices may also have unintended consequences on grid parameters, PQ, and system reliability. Power electronic devices, such as inverters, rectifiers, and voltage regulators, can produce high-frequency harmonics and transient disturbances that may result in voltage and current waveform distortion, voltage surges, and electromagnetic interference [10]. These disturbances can propagate throughout the power system, leading to PQ issues that can negatively impact end-users and result in equipment damage and premature failure. Furthermore, the integration of these devices into the power system can also lead to challenges related to system stability and reliability. The dynamic interaction between power electronic devices and the power system can result in oscillations, resonance, and voltage instability, which can cause system-wide disturbances and outages [11]. Therefore, it is imperative to carefully consider the integration of power electronic devices into the power system and to employ appropriate mitigation strategies to minimize their potential impacts on grid parameters, PQ, and system reliability.

Over the past years, distributed flexible AC transmission system (D-FACTS) technology has gained significant attention for its role in efficient energy utilization, demand control, voltage stabilization, PQ enhancement, power factor correction, and harmonic mitigation [12]. Moreover, D-FACTS technology offers additional applications such as power flow control, voltage regulation, reactive power compensation, improvement of transient and steady-state voltage stability, reduction of power losses, and overall power conditioning and quality improvement. The integration of D-FACTS technology has proven to be instrumental in enhancing the performance and reliability of power systems while effectively addressing challenges associated with energy utilization and PQ [13]. The concept of FACTS was introduced in the late 1980s to optimize the utilization of power system resources. At its core, FACTS devices employ high-voltage power electronics to regulate real and reactive power flow as well as voltage in the transmission system. By employing these technologies and strategies, power system operators can enhance PQ and improve the overall efficiency of the transmission network [14].

In recent years, numerous studies have focused on investigating the costs associated with voltage sags in power grid and exploring various mitigation techniques. Voltage sags, characterized by a temporary reduction in voltage magnitude, pose significant challenges to the reliable operation of power systems and can result in severe economic losses. Understanding the financial implications of voltage sags and identifying effective mitigation strategies are crucial for ensuring a stable and high-quality power supply. In reference [15], proposes an optimal configuration method for power quality monitors (PQMs) to effectively detect voltage sags. The method involves several steps. Firstly, a co-connectivity observation-based integer linear programming approach is used to identify multiple optimal schemes, considering all relevant state variables. Secondly, a decision tree is employed to further refine the PQM deployment scheme with improved accuracy in voltage sag detection. This is achieved by analyzing a large dataset of fault data generated through simulation software. Thirdly, three indicators for PQM monitoring are defined based on user requirements, and the performance of each PQM configuration scheme is comprehensively evaluated using a weighting method.

According to [16] focuses on deriving analytical expressions to calculate the magnitude of voltage sags resulting from faults in meshed or radial power networks. The study considers both balanced and unbalanced faults, while also accounting for the impact of power transformers. The paper compares three different methods for the stochastic assessment of voltage sag magnitude using the derived expressions: the method of critical distances, the method of fault positions, and the Monte Carlo method. In reference [17] focuses on the assessment of voltage sag and swell events in power systems. The authors propose a method to determine voltage sag/swell energy index matrices and use them to develop pivotal line assessment indicators based on energy index from the grid side. Additionally, fragile bus assessment indicators are proposed for assessing vulnerable buses. For the load side, a voltage swell influence degree function is proposed, and voltage sag/swell influence degree matrices are determined.

A recent research paper [18] introduces a data mining method for assessing the risk of voltage sag severity using the direct hashing and pruning (DHP) algorithm and replaceable coefficient. The DHP algorithm, which incorporates direct hashing and pruning techniques, is employed to mine the relationship between voltage sag characteristic attributes in fault scenarios and the voltage sag severity (VSS) of nodes. This approach enables the efficient identification of frequent item sets and enhances mining efficiency. The obtained association rules are matched with actual fault scenarios using replaceable coefficients, which allows for the determination of the VSS of real-world fault scenarios. Simulation and examples are used to validate the effectiveness and accuracy of the proposed method. In reference [19], a fuzzy logic controller is employed to address PQ issues. The proposed system is compared with existing methods, and the results demonstrate that the proposed method outperforms the existing techniques found in the literature. This highlights the superiority of the proposed approach in mitigating PQ issues, offering potential improvements in power system performance and reliability. More recent work by [20] focuses on the inclusion of hybrid energy storage systems (HESS), consisting of photovoltaic modules, fuel cells, and lithium batteries, within the PG. The HESS effectively regulates voltage and reduces costs, offering a conceptual framework for enhancing a superior power grid by eliminating voltage sag. The phase-locked loop (PLL) and synchronous reference frame (SRF-PLL) play a crucial role in the control and operation of inverters in the power grid, contributing to improved PQ through the implementation of D-FACTS technology.

The article highlights the significant contribution of addressing the cost and mitigation techniques associated with voltage sag in the power grid. The reliability and efficiency of electrical systems heavily rely on effectively managing voltage sag events, as they can lead to substantial financial losses, equipment damage, production downtime, and customer dissatisfaction. To minimize the impact of voltage sag incidents, various mitigation methods have been developed, including dynamic voltage restorers, uninterruptible power supplies, and voltage regulators. These techniques consider different cost factors such as equipment installation and maintenance expenses. Evaluating the cost-effectiveness of mitigation techniques becomes crucial for power grid operators and stakeholders, who must carefully assess them based on specific requirements and operational constraints. Ongoing advancements in power electronics, control systems, and energy storage technologies offer new opportunities for cost-efficient voltage sag mitigation. Research and development efforts focus on optimizing mitigation techniques, improving their performance, and reducing associated costs. By (injecting and absorbing) active and reactive power into distribution networks, D-FACTS devices play a crucial role in maintaining voltage stability, improving PQ indicators, and protecting sensitive loads from voltage fluctuations. Integration of advanced power electronics, intelligent control strategies, and energy storage systems further enhances the capabilities of D-FACTS technology. Continuous research and development efforts strive to explore innovative techniques that enhance the performance and efficiency of D-FACTS devices. With their remarkable contributions, D-FACTS technology contributes significantly to ensuring a reliable and high-quality power supply, meeting the growing demands of the modern power grid. The continuous advancement in this field promises to further enhance the management of voltage sag, PQ, and system stability, ultimately benefiting power grid operators and the overall electrical infrastructure.

The rest of the paper is organized as follows: **Section 2** provides an overview of the challenges related to PQ issues in electrical power systems. **Section 3** delves into the definition of voltage sag and presents various methods for estimating its magnitude and duration. **Section 4** focuses on the causes, propagation characteristics, and classification of voltage sag. It explores the diverse factors contributing to voltage sag occurrences, and their behavior during transmission and distribution, and presents a classification framework for different types of voltage sag events. **Section 5** investigates assessing the financial impact of voltage sag. **Section 6** explores various voltage sag mitigation techniques. This section provides insights into practical approaches for mitigating voltage sags and enhancing PQ. **Section 7** highlights the role of D-FACTS technology in addressing voltage sag issues. Finally, in **Section 8**, the paper concludes by summarizing the key findings and contributions.

2. Challenge PQ issues

Addressing power quality (PQ) issues are critical for ensuring the reliable and efficient operation of modern power systems. The consequences of PQ issues can be severe, including equipment failures, safety hazards, and decreased customer satisfaction. As a result, there have been significant contributions made in recent years to address PQ challenges and improve the overall performance of the power grid. One significant contribution has been the development of advanced PQ monitoring and control technologies [21,22]. These technologies allow power system operators to detect, diagnose, and mitigate PQ issues in real-time, improving the system's resilience and responsiveness to disturbances. Another significant contribution can be the development of power electronic devices that are specifically designed to improve PQ. Additionally, advancements in smart grid technologies, such as distributed energy resources and demand response programs, can help improve PQ by enabling more flexible and responsive management of electricity supply and demand [23,24]. Thus, the development and implementation of PQ standards and regulations have been a significant contribution to addressing PQ challenges. These standards guide acceptable levels of PQ and establish requirements for power system equipment and operation. By developing and enforcing these standards, power system operators can ensure that PQ issues are addressed consistently and effectively throughout the system. Improving PQ necessitates the integration of technological solutions to address existing problems, such as voltage sags, current disturbances, harmonics, and unbalancing. Table 1, presents the most common PQ issues in the power grid.

Table: 1. The most common PQ issues in the power grid include (issue, definition, and causes) [25-32].

Issue	Definition	Causes	Role D-FACTS?
Voltage sag	When V_{rms}> < V_{nom} from 10% to 90.0% for 0.50 cycles to 60 seconds.	▪ Failure in large motors start-up ▪ Customer's installation faults ▪ Poor system maintenance ▪ System faults	Yes
Voltage swell	When V_{rms}> V_{nom} from 10% up to 80% for 0.5 cycles to 60 seconds.	▪ Badly designed power sources ▪ Load switching ▪ Defectively regulated transformers ▪ Badly designed power sources	Yes
Variable fluctuation	Repeated fluctuations in V_{rms} from 90% up to 110% of V_{nom}	▪ Leading cause of frequent switching ▪ The root cause of welding plants ▪ Determine the cause of arc furnaces	Yes
Long interruptions	while electrical power supply interruptions occur for > 1s or 2s duration of time	▪ Poor coordination of protection devices ▪ Failure in equipment and fire	Yes
Harmonic	The voltage or current waveform frequencies are multiple fundamental such as non-sinusoidal waveforms.	▪ The immediate cause of system resonance ▪ Non-linear loads utilized of tool generating non-sinusoidal currents	Yes

V_{rms} refers to RMS voltage, V_{nom} knows as nominal voltage, μs knows as micro-seconds, ns refers to nano-second

3. Voltage Sag Definition and Estimation

The term voltage sag is defined according to IEEE 1159 which proved scientifically that such phenomena exist [33]. Voltage sag is a relative phenomenon of PQ in which the RMS value of the voltage magnitude drops below 0.9 (p.u.) in a period of time less than 60 seconds [34-38]. Figure 1, shows the voltage sag characteristics. Figure 2, displays a rectangular voltage tolerance curve that illustrates the voltage tolerance limits for electrical equipment. The curve shows that when voltage sags occur and their duration exceeds the duration threshold (T_{max}) and their depth exceeds the voltage magnitude threshold ($V_{\min}$), the equipment may trip or malfunction.

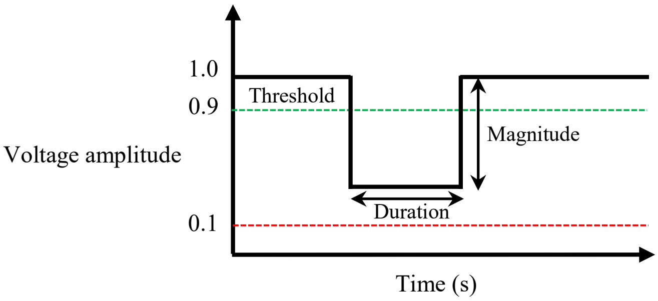


Figure 1. The voltage sag characteristics

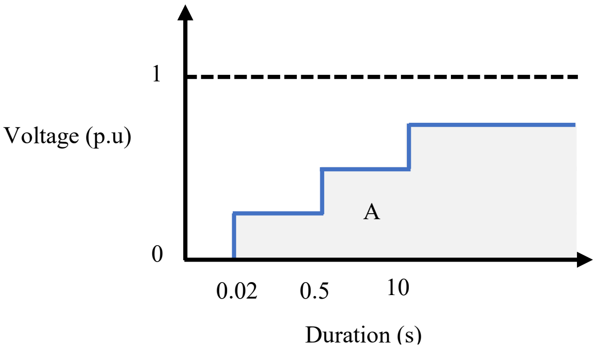


Figure 2. Equipment voltage tolerance curve [31].

The scientific evidence provided by IEEE 1159 confirms that PQ issues, including voltage sags, have a significant impact on power systems. This is evident given the critical role that PQ plays in the overall operation of the system [39-42]. Voltage sag is a PQ issue that occurs when a short circuit occurs in the power system, such as a single-phase or three-phase fault. In recent years, there has been growing recognition of the importance of addressing voltage sag issues in the power grid. This is due to the potential negative effects that voltage sags can have on the performance and reliability of power systems, including equipment damage, downtime, and lost productivity. As a result, voltage sag mitigation strategies have become increasingly important for power system operators to ensure the reliable and efficient operation of the power grid. In this direction, the IEEE 1100-2005 presents PQ as a theory for powering and grounding sensitive electronic devices in a manner that is appropriate for the operation of power grid equipment. Furthermore, IEEE 1159-2009 addresses voltage sag and voltage swell issues that are commonly observed in PQ. Voltage sag is a phenomenon that can rapidly deteriorate PQ, leading to poor power on the distribution network [43-49]. This can cause significant damage to the power system by decreasing the supply voltage magnitude and altering the amplitude of the voltage. Voltage sag can be calculated using the following formula:

$$U_{Sag} = \frac{Z_L + Z_F}{Z_S + Z_T + Z_L + Z_F} * 1.0 \ (p.u) \tag{1}$$

where U_{Sag} indicates the voltage sag magnitude. Z_L deals with power grid feeder impedance from the substation to the fault location. Z_F presents fault impedance. Z_S shows source impedance. transformer impedance known as Z_T.

To estimate the impacts of voltage sags on sensitive loads and the resulting financial losses, it is crucial to understand the boundary of sensitive loads. This boundary represents the voltage tolerance limits of the equipment and determines the level of voltage sag that the equipment can withstand without experiencing shutdowns or malfunctions. The immunity curves are useful tools for assessing the limits of sensitive loads against voltage sags. The immunity curves, such as ITIC, CBEMA, and SEMI F47, are graphical representations of the voltage tolerance limits of electrical equipment. These curves are typically provided by equipment manufacturers and are used to assess the level of voltage sag that the equipment can tolerate without tripping or malfunctioning. Figure 3 shows the Semiconductor Equipment and Materials International (SEMI) curve, which is an example of an immunity curve. The SEMI curve is a graphical representation of the voltage tolerance limits for semiconductor equipment. The curve shows that if the voltage falls into area A (i.e., below the SEMI curve), it can cause the mal-operation of semiconductor equipment.

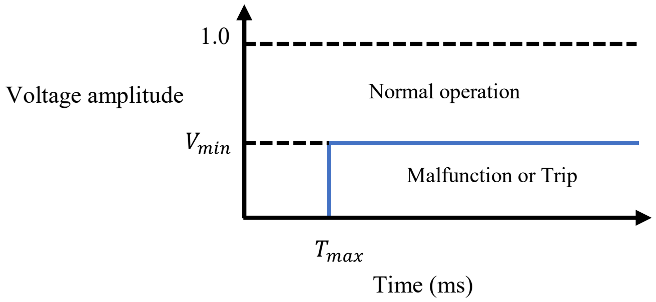


Figure 3. The SEMI immunity curve [32].

The immunity curves, including the SEMI curve, are essential tools for power system operators to assess the impact of voltage sags on sensitive loads. These curves can help identify the voltage tolerance limits of equipment and determine the level of voltage sag that is acceptable without causing malfunctions or shutdowns. By using immunity curves to assess the voltage tolerance limits of equipment, power system operators can implement targeted mitigation strategies to minimize the impact of voltage sags on sensitive loads and reduce the associated financial losses.

4. Causes, Propagation, and Harm of Voltage Sag

Voltage sag, also known as a momentary or temporary voltage dip, is a common PQ issue that can have adverse effects on electrical equipment and industrial processes. The causes of voltage sag can vary from faults in transmission lines and transformers to the starting of large motor loads. The propagation characteristics of voltage sag, including amplitude, duration, and frequency, can vary depending on the location and type of fault [50-56]. Understanding the classification of voltage sag is essential for developing effective mitigation strategies. This section provides an analysis of the causes, characteristics, propagation, and impact of voltage sags. The subsequent subsections will elaborate on each of these aspects.

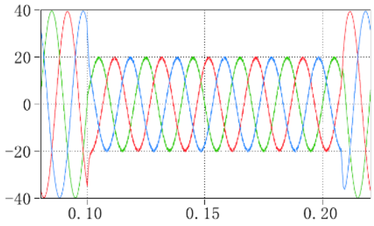
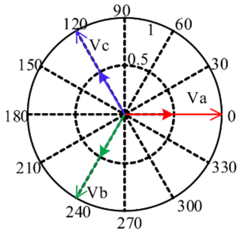
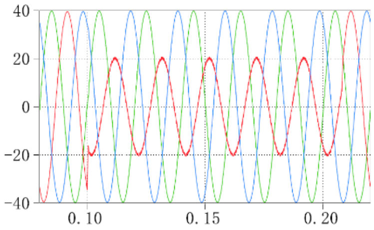
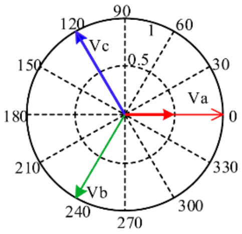
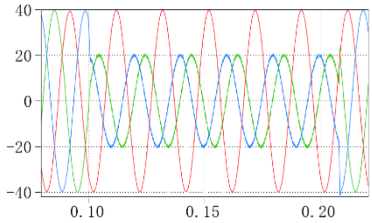
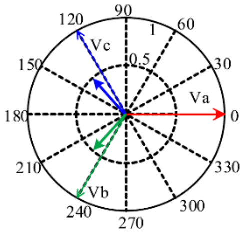
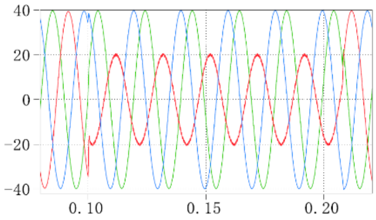
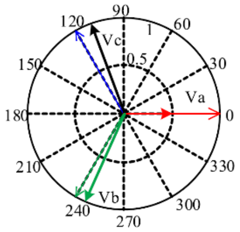
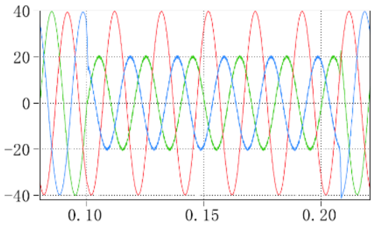
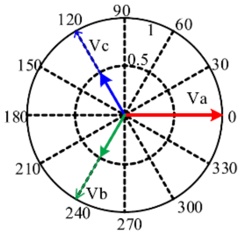
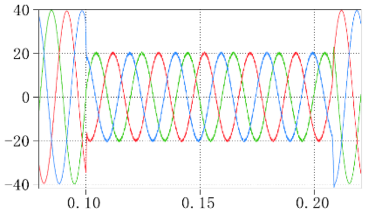
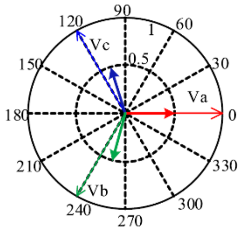
A. Causes of Voltage Sag

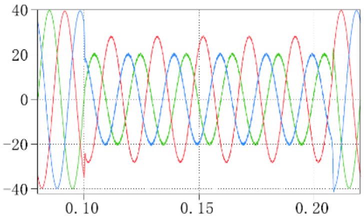
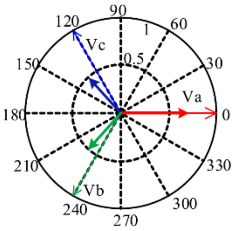
The primary types of short circuit faults are single-phase grounding short-circuits, two-phase interphase short-circuits, two-phase grounding short-circuits, and three-phase grounding short-circuits. These faults occur with a probability of approximately 70%, 15%, 10%, and 5%, respectively. Typically, voltage sags are more severe and pose a greater threat to sensitive electrical equipment, the closer the fault is to the point of failure.

B. Propagation of Voltage Sag

Voltage sag occurrences are primarily attributed to short circuits in nearby or distant electrical networks, which can result from symmetrical or asymmetrical faults [33,35]. These faults can be transformed into various forms through transformers. Table 2, presents the various types of voltage sags denoted as A-G, which can be transformed into other types when passing through coupling transformers. The table also includes waveform and phasor diagrams. By using the transfer matrix of transformers and the classification of sag voltages, one can easily determine the transformation of voltage sag types when passing through coupling transformers.

Table 2. Characteristic waveforms and phasor diagram of voltage sag [33,35].

Type	Waveform	Phasor diagram
A		
B		
C		
D		
E		
F		

G		

D. Harm of Voltage Sag

Transient PQ issues such as voltage sags can directly affect or even disrupt the normal power supply to users, resulting in severe economic losses. This issue is of utmost concern for sensitive customers. Voltage sags have the potential to cause harm to economic and industrial processes, leading to electrical failures. Typically, the impact of voltage sags is more significant in the information industry, large sensitive users, high-tech users, and power electronic devices. Presently, research in this area focuses on two aspects: system stability and reliability, and equipment performance enhancement under various grid voltage sag disturbance conditions. The voltage sag resulting from motor starts, as mentioned earlier, can harm adjacent motors and generators. In industrial settings, voltage sag occurrences can significantly impact the manufacturing process, leading to an increase in product disqualification rates and economic losses. Any production loss and associated costs due to voltage sags can significantly reduce the customers' product income [36-39]. The semiconductor and integrated chip (IC) manufacturing industries are particularly susceptible to the effects of voltage sags, as is the information industry. It is estimated that voltage sags are responsible for over 45% of data loss and errors on the client side, and more than 80% of server faults.

5. Assessing the Financial Impact of Voltage Sag

Voltage sags in the power grid can result in significant costs that can impact the reliability and efficiency of the power system. These costs can be classified into direct and indirect costs. Costs associated with voltage sags in the power grid include the cost of equipment damage, downtime, and lost productivity. Voltage sags can damage equipment, cause it to fail, and result in costly repairs or replacements. They can also cause downtime, leading to lost productivity and revenue. The cost of repairing or replacing damaged equipment can be significant, particularly for large industrial equipment. Moreover, voltage sags can cause downtime, which can result in lost productivity and revenue. For example, a voltage sag that disrupts the operation of a data center or manufacturing plant can result in lost production time and delayed shipments, leading to reduced profits.

Several studies aim to investigate the costs associated with voltage sags in power grid. According to a statistic published by the Electrical Power Research Institute (EPRI) in the USA, the use of sensitive electronic equipment and controls has significantly increased the costs associated with power disturbances. The research [40] shows that the cost of typical power disturbances has increased from around USD$1 billion in the 1990s to approximately USD$10 billion per annum. In [41], addressing the issue involves incorporating an active filter as a compensating device with a rated power of 120 kVA. The lifetime cost estimation for this solution over ten years amounts to 55,500 USD, including 43,500 USD for the active filter components and 12,000 USD for the circuit energy losses.

In reference [42,43], during the one-year monitoring period, the total cost of voltage sag was estimated to be US$ 4.04 million. This investigation is highly dependent on the cost of non-supplied energy per MWh, which was estimated to be US$ 2800/MWh. For the semiconductor industrial load with an annual energy consumption of 100 MWh, the cost incurred per interruption event is $50,000. By implementing the proposed solution, the number of equivalent interruption events reduces from 11 to 8.8, resulting in a reduced disturbance cost of $154,000 instead of $192,500. This issue has been considered by recent work [44] that analyzed the impact of voltage sags on consumer units in China and used questionnaires or personal interviews to calculate the resulting losses. The study found that the cost per voltage sag varied significantly across industrial sectors, which was mainly attributed to the final product's added value. For instance, in the chemical fiber industry, the costs ranged from US \$29,000.00 to US \$172,000.00, whereas, in the semiconductor industry, the costs varied from US \$574,000.00 to US \$3,585,000.00.

Assume that a manufacturing plant experiences a voltage sag that causes a production line to shut down for 2 hours. The plant operates 24 hours a day, 7 days a week, and has an estimated production capacity of 500 kW. The cost of electricity is 0.10 \$ per kWh, and the estimated loss of production due to the voltage sag is 20% (D=20%). The efficiency of the system is assumed to be 95% (η= 95%). Eq. (2) calculates the financial impact of the voltage sag as follows.

$$L = (P \times H \times D \times C) / (1000 \times \eta) \tag{2}$$

P = 500 kW x 20% = 100 kW (the power lost due to the voltage sag)

H = 2 hours, D = 20%, C = \$0.10 per kWh, η = 95%

L = (100 kW x 2 hours x 20% x \$0.10) / (1000 x 95%) = 0.42 \$

Therefore, the estimated financial impact of the voltage sag on the manufacturing plant is 0.42 \$. The plant may choose to implement mitigation measures, such as installing voltage regulators or backup power supplies, to reduce the likelihood and impact of voltage sags in the future. The efficiency of the system has an important impact on the financial impact of voltage sag. Efficiency is a measure of how much of the input power is converted into useful output power. In electrical systems, there are losses due to resistance in the wires, transformers, and other components, which reduce the efficiency of the system. When voltage sag occurs, the efficiency of the system may be reduced due to the increased current flow that is required to maintain the same level of power output. This increased current flow results in additional losses due to resistance, which further reduces the efficiency of the system. The financial impact of voltage sag is directly proportional to the power lost due to the sag, as well as the cost of electricity. However, the financial impact is inversely proportional to the efficiency of the system, because a more efficient system will require less input power to produce the same output power, and therefore will experience less power loss due to the sag.

6. Voltage Sag Mitigation Methods

Voltage sag mitigation techniques are methods used to reduce or eliminate the impact of voltage sags on power systems. These techniques are essential for ensuring reliable and efficient power system operation and minimizing the financial losses associated with voltage sags. Some of the common voltage sag mitigation techniques are demonstrated in the following Table 3.

Table 3. Voltage sag mitigation methods.

Ref.	Year	Description	Mitigation Methods	Software
[45]	2023	▪ The integration of the proton exchange membrane fuel cell (PEMFC) with the electrical power grid (EPG) offers the potential to enhance the PQ by providing the necessary power injection. However, this integration also introduces complications due to the adverse effects of voltage sag on the EPG. Conventional P-I controllers prove ineffective in addressing the voltage sag issue. In light of this, this research paper proposes the utilization of advanced equilibrium optimizer (AEO) and particle swarm optimization (PSO) controllers to mitigate voltage sag in an interconnected PEMFC-EPG system. ▪ The effectiveness of these advanced controllers is demonstrated by comparing their performance with that of conventional P-I controllers. Through this comparative analysis, the research highlights the efficiency and efficacy of the AEO and PSO controllers in addressing voltage sag and improving the overall PQ of the system.	P-I controllers AEO PSO	MATLAB

[46]	2023	▪ This paper focuses on mitigating voltage sags resulting from low-impedance faults. The proposed approach involves dividing the system into clusters of Microgrids (IEEE 33-bus) that can withstand the fault's impact and isolate the faulted area responsible for the voltage sag event.	Droop control	MATLAB
[47]	2022	▪ In this article, a single-phase dynamic voltage restorer (DVR) is proposed for the relief of voltage sags using compensation techniques such as in-phase compensation and phase-advanced compensation. ▪ DVR offers faster response times and improved accuracy, making it a viable option for distribution network operators.	the open-loop and the closed-loop control	PSCAD simulation
[48]	2022	▪ This paper proposed the doubly-fed induction generator (DFIG), which is often employed in wind energy conversion systems (WECSs). ▪ The algorithm is capable of detecting voltage events in single-phase, two-phase, and three-phase systems, whether they are symmetrical or asymmetrical, even if the supply voltage is distorted.	Hysteresis voltage control technique	Schematic and experimental setup
[49]	2022	▪ In this work, a wavelet correlation-based technique has been developed to select the most appropriate mother wavelet for the characterization and detection of voltage sag.	Mother wavelet selection technique	MATLAB
[50]	2022	▪ The proposed approach utilizes Gaussian naive Bayes (Gaussian NB) and K-nearest neighbors (K-NN) algorithms to determine the relative location of voltage sags. In comparison, support vector machine (SVM) and artificial neural network (ANN) methods are also evaluated. ▪ The findings indicate that K-NN and Gaussian NB algorithms achieve 98.75% and 97.34% accuracy, respectively, in determining the relative location of voltage sags.	Gaussian NB K-NN SVM ANN	MATLAB
[51]	2022	▪ The current paper introduces a DVR controller that employs the Least Mean Fourth (LMF) algorithm. The proposed controller is designed to mitigate voltage-related PQ problems, such as balanced and unbalanced voltage sags, voltage harmonic distortion, and balanced and unbalanced swells.	LMF	MATLAB
[52]	2021	▪ The primary objective of this paper was to mitigate voltage sags through the integration of fuel cells (with the distribution network system using a distribution static synchronous compensator system, which was accomplished.	Fuzzy logic controller	MATLAB
[53]	2021	▪ The article explores the application of a dual-slope delta modulation (DSDM) technique to regulate a dynamic voltage restorer (DVR), which can effectively address voltage sag issues in power systems. ▪ According to the simulation results, the suggested DSDM technique is proficient in mitigating voltage sags by precisely injecting the necessary voltage in both magnitude and phase angle, thereby demonstrating its effectiveness.	DSDM technique	MATLAB
[54]	2020	▪ This paper suggests a Dynamic Voltage Restorer (DVR) as a cost-effective solution for compensating voltage sags and safeguarding critical loads against both balanced and unbalanced sag voltages. The proposed DVR topology utilizes a control strategy, such as a PI controller, and is evaluated through MATLAB/Simulink simulations to assess its performance.	PI controller	MATLAB

[55]	2019	▪	The paper proposes an effective and enhanced particle swarm optimization (PSO) technique to optimize the gain parameters of the PI controller. The DVR's performance and efficacy are verified through MATLAB simulations and the utilization of Sim Power Systems Blocksets.	PSO technique	MATLAB

In this context, significant contributions have been made in the field of voltage sag mitigation techniques, addressing the challenges associated with PQ and ensuring the reliable operation of electrical systems. These contributions include:

- Advanced Power Electronics: The development of advanced power electronic devices, such as DVRs and UPQC, has revolutionized voltage sag mitigation. These devices offer precise and rapid compensation capabilities, effectively mitigating voltage sags and maintaining the quality of the power supply.
- Energy Storage Systems (ESS): ESS, including batteries and Supercapacitors, have emerged as valuable tools for voltage sag mitigation. Their ability to provide instant and reliable power support during voltage sags helps stabilize the system and protect sensitive loads from disruptions.
- Intelligent Control Strategies: The application of intelligent control strategies, such as fuzzy logic control, neural networks, and adaptive control algorithms, has greatly improved the performance of voltage sag mitigation techniques. These strategies enable real-time monitoring and accurate compensation, enhancing the efficiency and effectiveness of voltage sag mitigation.
- Integration of Distributed Generation: The integration of distributed generation, such as renewable energy sources and Microgrids, has contributed significantly to voltage sag mitigation. These distributed generation systems can supply additional power during voltage sags, reducing the impact on the grid and enhancing system stability.
- Fault Ride-Through Capability: The implementation of fault ride-through capability in power electronic devices and renewable energy systems has been a notable contribution to voltage sag mitigation. This capability allows devices to remain connected to the grid and continue supplying power during voltage sag events, minimizing disruptions and improving system resilience.
- Standardization and Guidelines: The development of standards and guidelines for voltage sag mitigation techniques has provided a structured approach to implementation. These standards ensure consistency, interoperability, and reliable performance across different systems, promoting widespread adoption and facilitating the integration of voltage sag mitigation measures.
- Using Cooperative Control techniques to manage energy storage and compensate for voltage sag synchronously and effectively.
- Developing Multi-Level Voltage Sag Mitigation Systems that use a matrix of electronic devices to provide accurate and adequate voltage sag compensation.
- Develop simulation models of sensitive loads that can be used to evaluate the impact of voltage sag and determine the best strategy for voltage sag mitigation.
- Using Artificial Intelligence and Machine Learning techniques to analyze electrical data and improve the performance of voltage sag mitigation technologies.
- Implementing Smart Grid Technologies to improve electrical energy management and mitigate voltage sag in real-time.

In this direction, the significant contributions made in these areas have enhanced the effectiveness, reliability, and overall performance of voltage sag mitigation techniques. As a result, the power grid can now better withstand voltage sags, ensuring the continuous operation of critical equipment and reducing the economic losses associated with power disruptions.

7. D-FACTS Technology

Various methodologies are employed to enhance the PQ of distribution networks, with the most effective and successful approach being the utilization of distributed flexible AC transmission system (FACTS) technology [56-62]. D-FACTS technologies are considered equipment that can be used to rectify voltage sags in the power grid and is often modeled as such for assessment purposes. The efficacy of these devices in rectifying PQ metrics is heavily reliant on the performance of the control system [63,69]. The primary objective of D-FACTS technology is to restore and sustain voltage levels in scenarios where voltage drops occur at the point of connection for sensitive loads within a network. Microgrids that incorporate numerous micro sources are susceptible to reactive power fluctuations, which can result in instability if voltage control is not effectively managed. In such cases, a variety of compensators provided by D-FACTS technologies or a power system stabilizer can be employed to stabilize the grid. D-FACTS devices have garnered significant attention from researchers due to their prominent role in enhancing PQ within systems. Table 4, indicates several types of D-FACTS, controllers and parameters.

Table 4. The different types of D-FACTS controlled and the parameters [74-76].

Type	Characteristics	Controlled parameters	Technology	Power grid performance
Shunt	Control susceptance	Real & Reactive power	➢ Dynamic Voltage Restorer (DVR) ➢ Distributed Static Synchronous Compensator D-STATCOM ➢ Static Synchronous Compensator (STATCOM) ➢ Static VAR Compensator (SVC)	Voltage sag
Series	Control reactance	Real & Reactive power	➢ Sub-Synchronous Series Compensator (SSSC) ➢ Thyristor Controlled Series Capacitor (TCSC)	Voltage sag
Series- Series	Control V & δ	Real & Reactive power	➢ Interlink Power Flow Controller (IPFC) ➢ Generalised Interlink Power Flow Controller (GIPFC)	Voltage sag
Shunt-Series	Control $X, V \text{ and } \delta$	Real & Reactive power	➢ Unified Power Flow Controller (UPFC) ➢ Unified Power Quality Conditioners (UPQC)	Voltage sag

It is worth mentioning that D-FACTS technologies are typically implemented in distributed grid, where they can be deployed at various locations within the network to enhance power system performance. D-FACTS technologies can be installed at strategic points in the distribution system to provide voltage and reactive power control, improve power quality, and enhance system stability [70-73]. On the other hand, Power System Stabilizer (PSS) controllers are primarily implemented in large central power plants. PSS is a control device that is integrated into the excitation system of synchronous generators to improve the dynamic stability of the power system. The main purpose of a PSS controller is to provide damping to power system oscillations and improve the response of the synchronous generators during disturbances.

In the context of the power grid, the utilization of D-FACTS technology facilitates the injection of both active and reactive power. In the case of shunt D-FACTS, the DVR, which is closely associated with the voltage-source converter, is employed to compensate for various PQ issues, including voltage sag, voltage unbalance, unbalanced loads, harmonics, and voltage fluctuations. Similarly, D-STATCOM serves a similar purpose [77,78]. On the other hand, shunt-series D-FACTS compensators incorporate Unified Power Quality Conditioners (UPQC) as an additional component to enhance the dynamic regulation of active and reactive power, mitigate voltage flicker, address voltage unbalance, and mitigate harmonic distortions. In this regard, the main purpose of DVR and D-STATCOM are to contribute to the power grid as quickly as possible with inductive or capacitive components to regulate the reactive power and voltage around presetting values that are adapted to its particular requirements, while also improving power transfer capability, the efficiency of the power transmission system and damping of the power and frequency oscillations. The increasing demand for electricity in many countries has led to the need for the expansion of transmission lines and electrical infrastructure, which requires significant capital investments [79,80]. Consequently, the search for effective solutions to reduce costs for electric utilities has become a major challenge in recent decades. Therefore, D-FACTS technology holds great promise as an effective solution for mitigating voltage sags in the power grid and improving PQ and stability.

8. Conclusion

The cost and mitigation techniques associated with voltage sag in power grids are of paramount importance in ensuring the reliable and efficient operation of electrical systems. Voltage sag events can result in significant financial losses due to equipment damage, production downtime, and customer dissatisfaction. Therefore, effective mitigation techniques are essential to minimize the impact of voltage sag incidents. Various methods, such as dynamic voltage restorers, uninterruptible power supplies, and voltage regulators, have been developed to mitigate voltage sag effects and maintain the quality of the power supply. These techniques involve different cost considerations, including equipment installation and maintenance expenses. It is crucial for power grid operators and stakeholders to carefully evaluate the cost-effectiveness of mitigation techniques based on their specific requirements and operational constraints.

Furthermore, the continuous advancements in power electronics, control systems, and energy storage technologies offer new possibilities for cost-efficient voltage sag mitigation. Ongoing research and development efforts focus on optimizing mitigation techniques, improving their performance, and reducing their associated costs. By implementing appropriate mitigation measures, power grid operators can enhance the reliability and resilience of their systems, minimize financial losses, and ensure the uninterrupted operation of critical electrical infrastructure.

However, D-FACTS technology, including devices such as DVR, D-STATCOM, and UPQC, has emerged as a significant advancement in the field of PQ and system stability. These devices provide effective solutions for voltage sag mitigation, voltage regulation, and compensation of PQ issues. By injecting active and reactive power into distribution networks, D-FACTS technologies help maintain voltage stability, improve PQ indicators, and protect sensitive loads from voltage fluctuations. The integration of advanced power electronics, intelligent control strategies, and energy storage systems has further enhanced the capabilities of D-FACTS technology. The ongoing research and development efforts in this field continue to explore innovative techniques and improve the performance and efficiency of D-FACTS technologies. With their remarkable contributions, D-FACTS technology plays a crucial role in ensuring a reliable and high-quality power supply, meeting the growing demands of the modern power grid.

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