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Power Quality Issues and Their Impact on Adjustable Speed Drives: Analysis and Mitigation

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Abstract - Power quality (PQ) has emerged as a critical factor affecting the reliability and performance of modern electrical systems. The widespread use of sensitive electronic equipment and power electronic converters has increased system vulnerability to disturbances such as voltage sag and swell. This paper presents a comprehensive analysis of PQ issues, their classification, causes, and consequences, with particular emphasis on voltage-related disturbances. The operational characteristics of Adjustable Speed Drives (ASDs) and their sensitivity to PQ variations are examined. The behaviour of DC-link voltage during disturbances and the associated tripping mechanisms are analysed. Finally, mitigation techniques are discussed to improve system reliability and performance.

Keywords: Power Quality (PQ), Voltage Sag and Swell, Adjustable Speed Drives (ASDs), DC-Link Voltage, Mitigation Techniques

1. INTRODUCTION

Modern industrial processes heavily depend on automated systems and power electronic devices, making them highly sensitive to deviations in supply voltage and frequency. Among various PQ disturbances, voltage sag and swell are the most frequently occurring and have significant impacts on industrial loads. Adjustable Speed Drives (ASDs), which are widely used for motor control, are particularly vulnerable due to their dependence on stable DC-link voltage. Therefore, a detailed understanding of PQ disturbances and their effects is essential for ensuring system reliability.

Recent advancements in power quality (PQ) research highlight the increasing importance of analysing voltage disturbances such as sag and swell due to their severe impact on modern power electronic systems and industrial loads [1]. A quantitative approach using the Taguchi method has been proposed to assess voltage sag-related economic losses, providing improved decision-making capability for industrial applications [2]. The impact of short-duration voltage variations on converter-based systems such as VSC-HVDC has been extensively studied, revealing significant vulnerability of power electronic interfaces to PQ disturbances [3]. Advanced signal processing techniques have been introduced for accurate voltage sag detection and compensation, improving the performance of custom power devices such as Dynamic Voltage Restorers (DVRs) [4].vWavelet packet transform-based approaches have been developed to enhance the feature extraction and classification accuracy of voltage sag events in real-time monitoring systems [5].

In electric vehicle charging infrastructure, novel detection techniques have been proposed to accurately estimate sag parameters including magnitude, duration, and phase angle under dynamic operating conditions [6]. Active Voltage Component (AVC)-based methods have demonstrated improved accuracy in detecting and characterizing voltage sag events with minimal computational error [7]. Multilevel inverter-based Unified Power Quality Conditioners (UPQCs) integrated with intelligent controllers have shown enhanced performance in mitigating sag, swell, and harmonic distortions in distribution systems [8]. Artificial intelligence-based approaches, particularly neural network-assisted controllers, have significantly improved adaptive compensation of PQ disturbances in modern smart grids [9].Comprehensive studies on voltage sag and swell characteristics indicate that switching operations and system faults remain the dominant causes of PQ disturbances in distribution networks [10].

The increasing penetration of distributed energy resources has led to a higher frequency of voltage sag events, particularly affecting sensitive loads in low-voltage distribution systems [11]. Time-varying signal analysis methods have been introduced for accurate identification of voltage sag events under dynamically changing system conditions [12]. Wavelet-based disturbance indices combined with machine learning algorithms have been proposed for efficient classification of multiple PQ events occurring simultaneously [13]. Deep learning-based unsupervised clustering techniques, such as autoencoders, have enabled accurate classification of PQ disturbances without requiring labelled datasets [14]. Overall, recent studies confirm that voltage sag remains the most critical power quality issue, causing equipment malfunction, industrial downtime, and significant economic losses, thereby necessitating advanced mitigation and ride-through solutions [15].

Power quality disturbances, particularly voltage sag and swell, continue to challenge the stability of modern electrical systems. The increasing use of power electronic devices and sensitive industrial loads amplifies the impact of such disturbances. Adjustable Speed Drives are especially vulnerable due to their reliance on stable DC-link voltage conditions. Therefore, a systematic understanding of disturbance characteristics and their effects is essential for reliable system operation.

In this paper, a comprehensive analysis of power quality issues and their classification is presented. Adjustable Speed Drives under voltage disturbances is critically examined and mitigation techniques are discussed.

3. CLASSIFICATION OF POWER QUALITY ISSUES

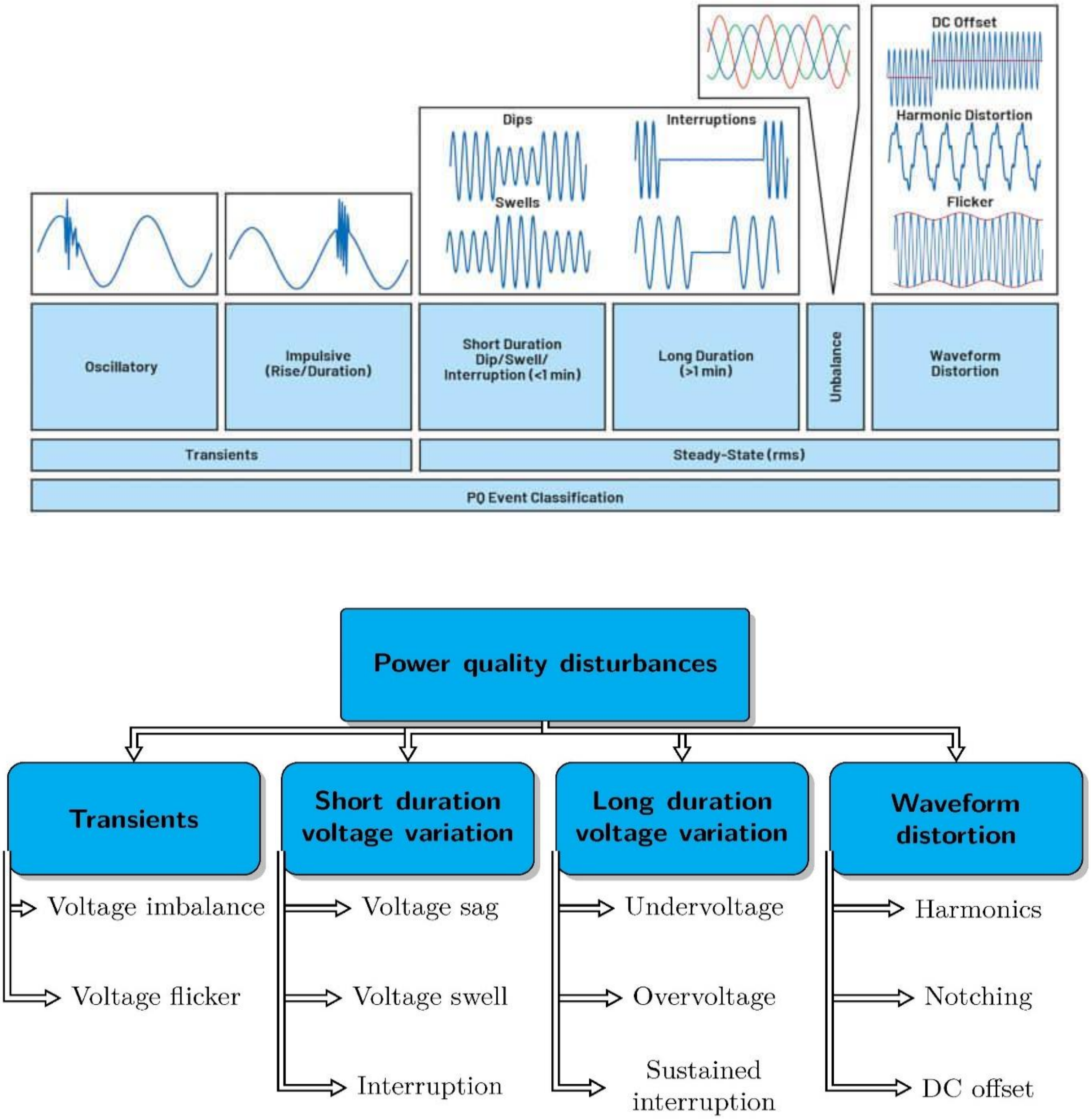


Figure 1. Classification of Power Quality Disturbances

Power quality disturbances are broadly classified into long-duration variations, short-duration variations, transients, and waveform distortions. The diagrams illustrate how different disturbances such as sag, swell, interruptions, harmonics, and transients are grouped based on their duration and characteristics. This classification is essential for identifying the nature of disturbances and selecting appropriate mitigation techniques. The simplified representation helps in understanding the relationship between different PQ phenomena and their impact on electrical systems.

4. POWER QUALITY STANDARDS

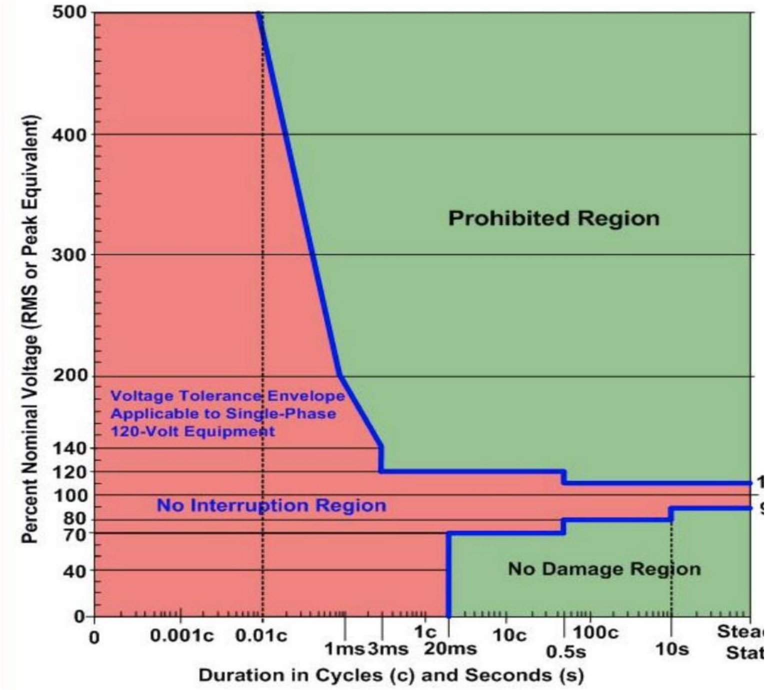


Figure 2. CBEMA Curve

The CBEMA curve represents the tolerance limits of electrical equipment to voltage variations over time. It defines acceptable regions where equipment operates normally and regions where malfunction or damage may occur. The curve shows that equipment can tolerate short-duration voltage deviations but becomes increasingly sensitive as duration increases. This graphical representation is widely used to evaluate the susceptibility of electronic devices to voltage disturbances.

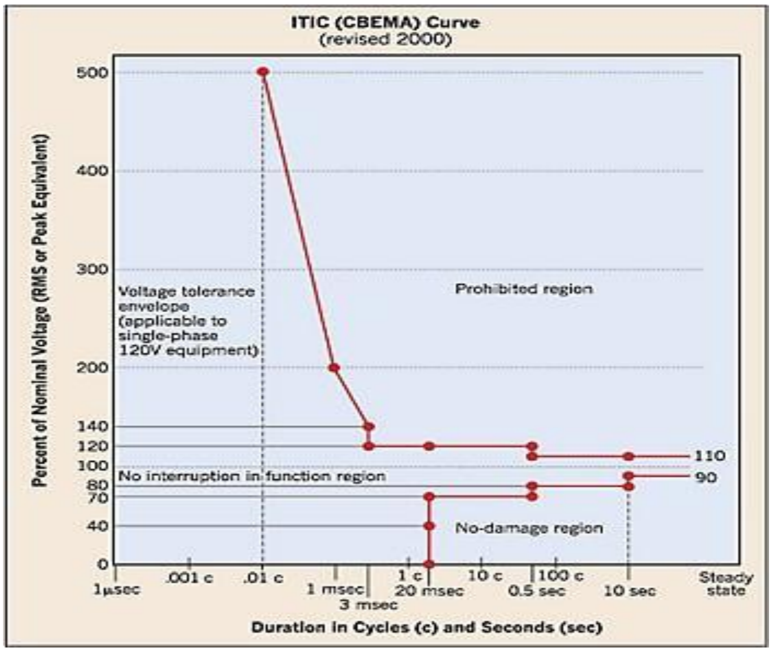


Figure 3. ITIC Curve

The ITIC curve is an updated version of the CBEMA curve and is commonly used for modern information technology equipment. It defines safe operating regions based on voltage magnitude and duration. When the voltage remains within the acceptable zone, equipment functions normally; however, deviations outside this region can lead to malfunction or permanent damage. The ITIC curve provides a more refined understanding of equipment sensitivity in contemporary power systems.

5. VOLTAGE SAG

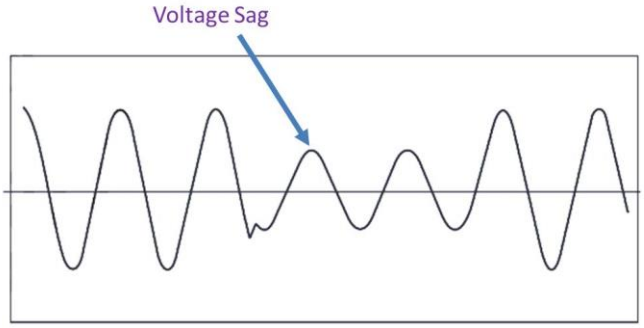


Figure 4. Voltage Sag Waveform

Voltage sag is characterized by a sudden reduction in RMS voltage magnitude, typically between 0.1 and 0.9 per unit, lasting from half a cycle to one minute. The waveform clearly illustrates the temporary drop in voltage and its recovery to normal levels. This disturbance is primarily caused by faults, motor starting, or transformer energizing. The graphical representation helps in visualizing how voltage sag affects the supply waveform and consequently the connected loads.

6. SAG CHARACTERIZATION

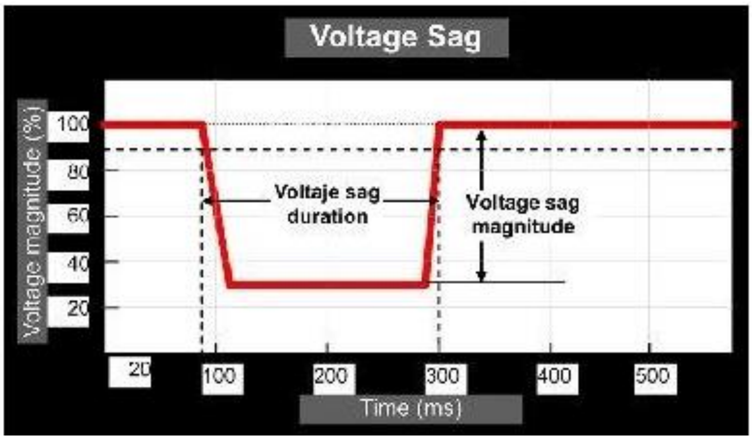


Figure 5. Sag Magnitude and Duration

Voltage sag is typically characterized using two parameters: magnitude (depth) and duration. The figure illustrates how different combinations of these parameters define the severity of the disturbance. Shallow sags with short duration may not affect equipment, whereas deep and long-duration sags can cause complete system shutdown. This representation is useful in evaluating equipment tolerance and designing protection schemes.

7. TYPES OF VOLTAGE SAG

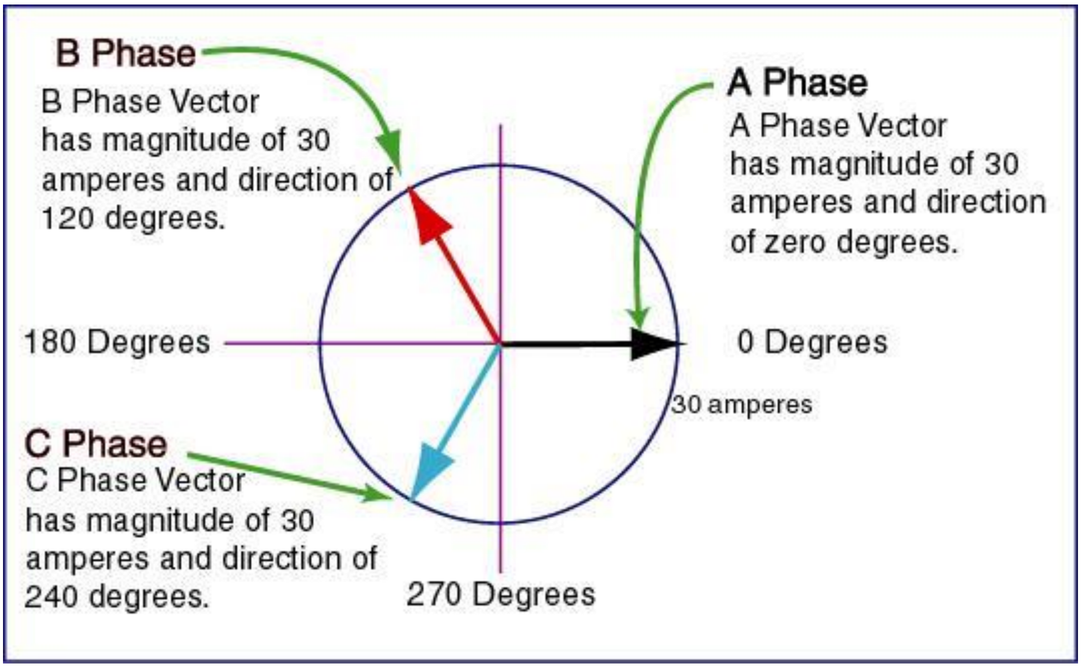


Figure 6. Types of Voltage Sag

Voltage sags are classified into different types based on the number of affected phases and phase angle displacement. The phasor diagrams illustrate how voltage magnitude changes across phases during different fault conditions. Balanced sags affect all three phases equally, whereas unbalanced sags impact one or two phases. Understanding these variations is crucial for analysing the behaviour of three-phase systems and designing mitigation techniques.

8. VOLTAGE SWELL

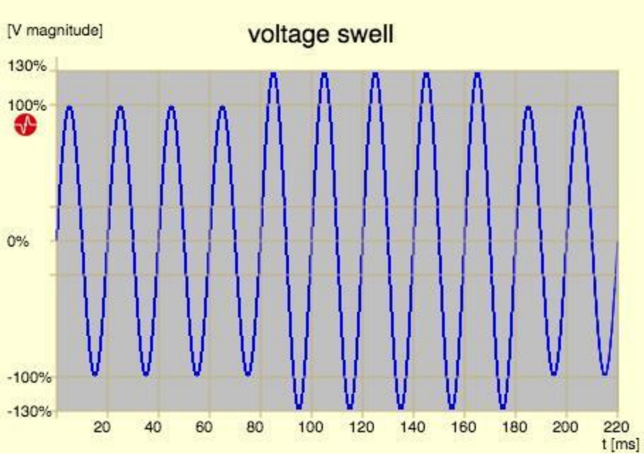


Figure 7. Voltage Swell Waveform

Voltage swell is the opposite of sag and is characterized by an increase in RMS voltage above the nominal value. The waveform shows how voltage rises temporarily before returning to normal levels. This phenomenon is typically caused by sudden load reduction, switching operations, or single-phase faults. Although less frequent than sag, voltage swell can cause insulation stress and damage to sensitive equipment.

9. ADJUSTABLE SPEED DRIVES

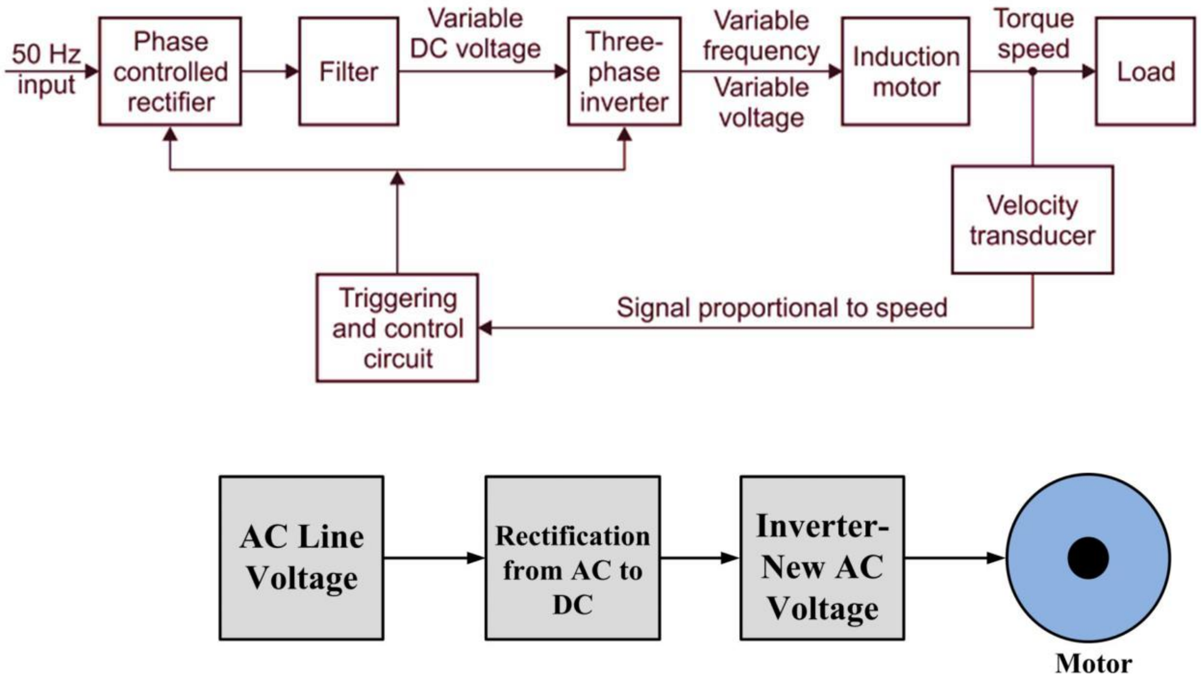
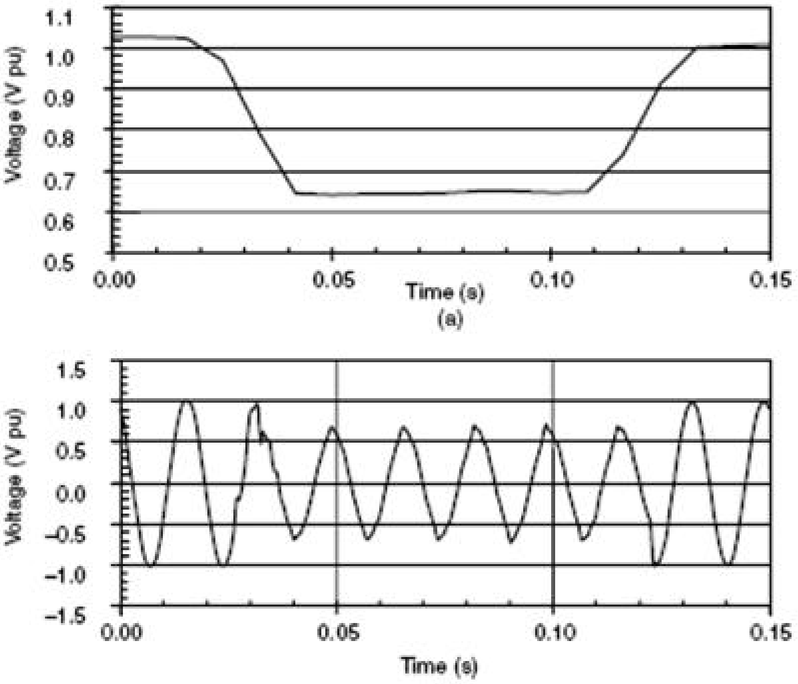


Figure 8. Adjustable Speed Drive (ASD) Block Diagram

The ASD block diagram illustrates the main components, including the rectifier, DC-link, inverter, and motor. The rectifier converts AC to DC, the DC-link stabilizes the voltage, and the inverter converts DC back to controlled AC. This configuration enables precise control of motor speed and torque. The diagram clearly shows the flow of power and highlights the importance of DC-link voltage stability in overall ASD operation.

10. DC-LINK VOLTAGE BEHAVIOUR



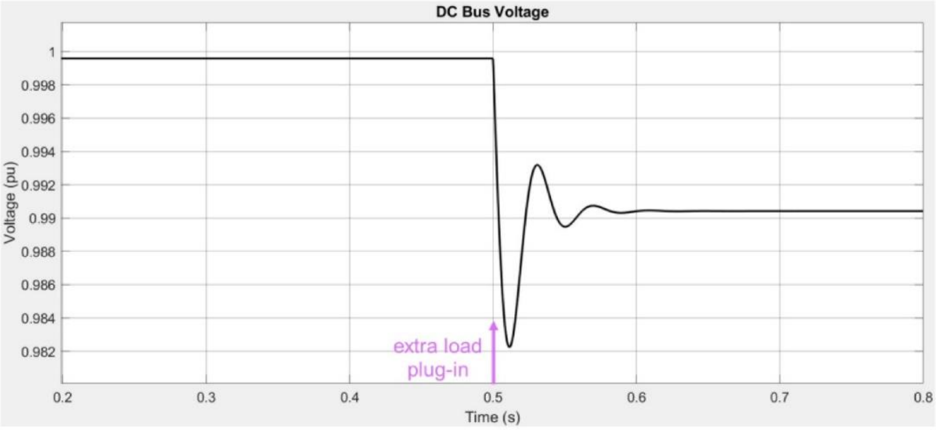
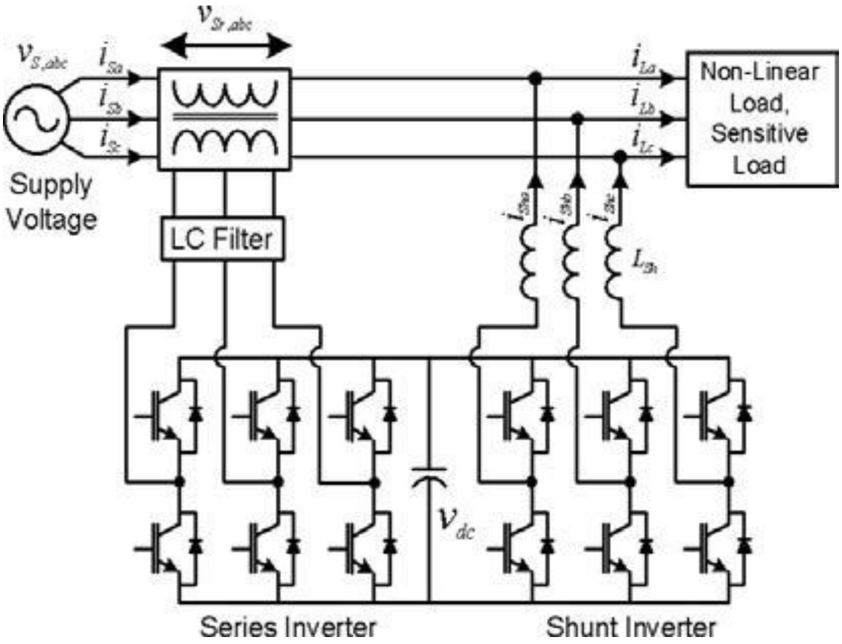


Figure 9. DC-Link Voltage During Voltage Sag

The figure illustrates the variation of DC-link voltage during a voltage sag event. As the supply voltage drops, the DC-link voltage begins to decrease due to reduced energy input. If the sag persists, the voltage may fall below the protection threshold, leading to ASD tripping. This behaviour highlights the critical role of DC-link capacitance and energy storage in maintaining system stability.

11. MITIGATION TECHNIQUES



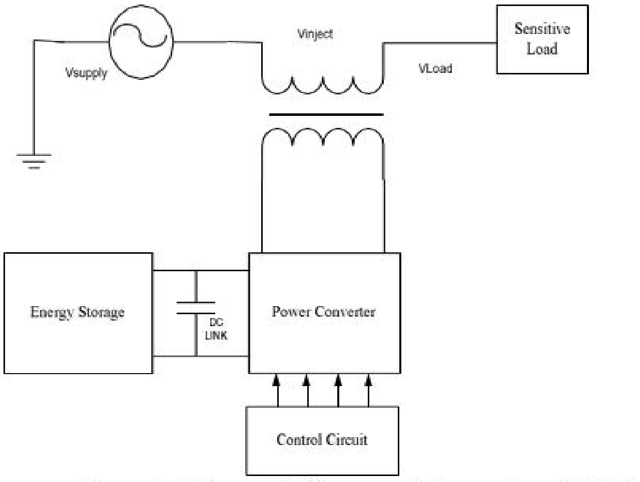


Figure 10. DC-Link Voltage Response During Voltage Sag

The figure shows the variation of DC-link voltage in an Adjustable Speed Drive (ASD) during a voltage sag condition. When the supply voltage drops, the DC-link capacitor begins to discharge due to reduced input energy. This results in a gradual decrease in DC-link voltage, affecting the inverter operation. If the voltage falls below a critical threshold, the protection system may trip the drive to prevent damage. Thus, maintaining DC-link voltage stability is essential for reliable ASD performance under disturbances.

UPQC - P DVR is used for series voltage injection in phase with supply current with only an active power injection.

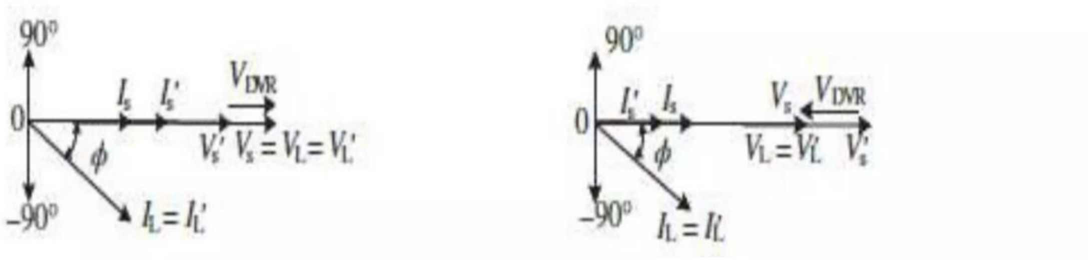


Figure 11. UPQC-P Phasor Diagrams for UPQC – P Voltage ag and Swell Compensation

The figure illustrates the phasor representation of voltage sag and swell compensation using a Unified Power Quality Conditioner (UPQC-P). During voltage sag, the UPQC injects a voltage component in phase with the supply to restore the load voltage to its nominal value. In contrast, during voltage swell, the UPQC injects a voltage component opposite in phase to reduce the excess voltage. This dynamic compensation ensures that the load voltage remains stable under varying disturbance conditions. Thus, the UPQC effectively protects sensitive equipment and improves overall power quality in the system.

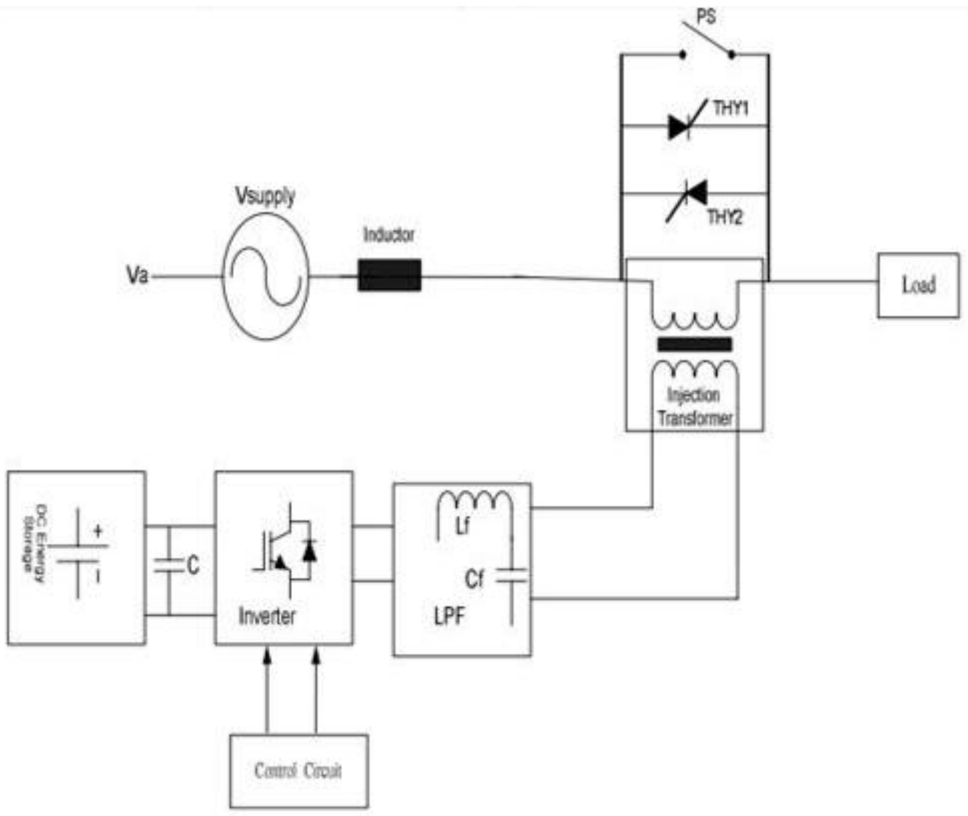


Figure 12. Power Quality Mitigation Techniques

The figure illustrates common mitigation devices such as Dynamic Voltage Restorers (DVR) and Unified Power Quality Conditioners (UPQC). These devices compensate for voltage disturbances by injecting appropriate voltage or current into the system. The diagram shows how these solutions are integrated into the power system to maintain voltage stability and protect sensitive loads.

12. CONCLUSION

Power quality disturbances, particularly voltage sag and swell, significantly affect the performance and reliability of industrial systems. Voltage sag is the most frequent disturbance and leads to DC-link voltage reduction, causing ASD tripping and production losses. Voltage swell, although less frequent, can cause severe damage to equipment. The increasing use of sensitive electronic devices necessitates the adoption of advanced monitoring and mitigation techniques. Future research should focus on intelligent control strategies and energy storage-based solutions to enhance ride-through capability and ensure uninterrupted operation.

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