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Enhancing Of Power Quality Issue in Utility Grid Using Dynamic Voltage Restorer (DVR)

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***Abstract*—Power quality disturbances, such as voltage sags, harmonics, and flickers, are growing concerns due to the increas- ing integration of nonlinear loads and renewable energy sources. The Dynamic Voltage Restorer (DVR) is an effective solution that injects compensating voltage to maintain stable supply conditions. This paper explores DVR operation, design, and control strategies, including PI control, for real-time applications. The implementation of DVR enhances grid stability, reduces downtime, and improves energy efficiency. Future advancements, such as integration with smart grids, renewable energy, and AI- based controls, are also discussed to enhance DVR performance in modern power systems.**

***Index Terms*—component, formatting, style, styling, insert**

I. Introduction

In modern power systems, maintaining high power quality is crucial for the efficient operation of electrical equipment and the overall stability of the grid. Power quality disturbances such as voltage sags, swells, harmonic distortions, flickers, and transients can lead to operational failures, equipment damage, increased energy losses, and financial setbacks. These disturbances are primarily caused by faults in transmission and distribution networks, sudden load changes, switching operations, integration of renewable energy sources, and non- linear loads such as variable frequency drives, power con- verters, and industrial machinery. With the rapid growth of industries and the increasing reliance on sensitive electronic equipment, ensuring a stable and high-quality power supply has become a major concern for utilities and consumers. Conventional solutions like uninterruptible power supplies (UPS), capacitor banks, and voltage regulators provide some level of compensation but often come with limitations such as high costs, maintenance complexities, and limited effec- tiveness in handling dynamic voltage disturbances. To address these challenges, the Dynamic Voltage Restorer (DVR) has emerged as a highly effective and efficient custom power device. DVR is a series-connected power electronic device designed to detect voltage disturbances and dynamically inject the required compensating voltage to maintain the desired power quality. Unlike traditional voltage regulation methods, DVR provides real-time compensation with high efficiency, low cost, and rapid response time, making it a preferred choice for modern power distribution networks. DVR operates by using a Voltage Source Inverter (VSI) and an energy storage system to generate the compensating voltage. It de- tects voltage sags or swells and injects the required voltage through a series-connected injection transformer, ensuring that the load voltage remains within the acceptable range. Advanced control strategies such as Proportional-Integral (PI) control, Synchronous Reference Frame (SRF) theory, and Artificial Intelligence-based techniques further enhance the DVR's ability to respond quickly and accurately to voltage disturbances.As power systems continue to evolve with the integration of renewable energy sources such as solar and wind power, smart grids, and distributed generation, power quality issues are expected to become more complex. DVR technology provides a reliable, scalable, and efficient solution to these challenges by improving voltage stability, reducing harmonic distortions, and ensuring uninterrupted power supply to critical loads. This report explores the importance of power quality in modern grids, the working principle of DVR, its components, control strategies, advantages, and its role in future power systems. By understanding the capabilities and benefits of DVR, power utilities and industries can adopt more robust solutions to ensure a stable, efficient, and high-quality power

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supply for various applications.

II. METHODS TO SOLVE POWER QUALITY ISSUE ON POWER GRID USING DVR

A. Voltage Injection techniques for Compensation, Energy Storage Methods for DVR, Control Strategies for DVR Op- eration

A. Voltage Injection techniques for Compensation:
The Dynamic Voltage Restorer (DVR) is an effective solu- tion for mitigating voltage disturbances such as sags, swells, and harmonic distortions in power grids. It operates by in- jecting a compensating voltage into the system to maintain the desired voltage level for sensitive loads. The method used for injecting this compensating voltage plays a crucial role in determining the DVR's effectiveness, efficiency, and energy consumption. Various voltage injection techniques are employed depending on the nature of the voltage disturbance, the available energy storage, and the system requirements. These techniques include Pre-Sag Compensation, In-Phase Voltage Injection, Voltage Tolerance Method, Quadrature In- jection, and Adaptive Voltage Injection, each of which has its advantages and applications. Advantages:

- Precise voltage restoration: It restores the supply voltage exactly to its pre-disturbance level, including both mag- nitude and phase angle.
- Prevents Equipment Malfunction: Highly effective for sensitive industrial applications where even minor voltage deviations can disrupt operations.
- Ensures Load Stability: Maintains power quality and prevents system instability caused by sudden voltage drops.

Disadvantages:

- High Energy Consumption: Requires significant energy storage capacity to inject the full compensating voltage.
- Expensive Implementation: Demands complex control algorithms and advanced sensors to track and restore the original voltage waveform.
- Less Efficient for Long Sags: May not be ideal for prolonged voltage sags due to limited energy storage availability.

B. 1.2.2 Energy Storage Methods for Dynamic Voltage Re- storer (DVR)

The Dynamic Voltage Restorer (DVR) is a power quality enhancement device that requires an efficient energy storage system to supply compensating voltage during disturbances such as voltage sags, swells, and transients. The effectiveness of a DVR depends on its ability to respond quickly and accurately to voltage disturbances, and this is largely deter- mined by the energy storage method used. The choice of an appropriate energy storage system affects the DVR's response time, efficiency, capacity, and overall reliability. Several energy storage technologies are available for DVRs, including battery energy storage systems (BESS), supercapacitors, flywheel en- ergy storage systems (FESS), and superconducting magnetic energy storage (SMES), each with distinct advantages and limitations. Advantages:

- High Energy Density: Batteries can store a large amount of energy, making them ideal for long-duration voltage compensation.
- Cost-Effective: Compared to other energy storage tech- nologies, batteries are relatively affordable and widely available.

C. LITERATURE SURVEY

Power quality is a critical aspect of electrical power systems, as voltage disturbances such as sags, swells, and harmonics can significantly affect industrial, commercial, and residential consumers. With the increasing integration of renewable en- ergy sources, electric vehicle charging stations, and nonlinear loads, maintaining stable voltage levels in the power grid has become more challenging. Various power conditioning devices, such as Dynamic Voltage Restorers (DVRs), have been studied extensively to mitigate voltage-related power quality issues. The following literature survey presents key findings from previous research on DVR design, control strate- gies, voltage compensation techniques, and energy storage methods. Numerous studies highlight DVR as an effective voltage compensation device to mitigate voltage sags, swells, and flicker in power distribution networks.
According to Hingorani and Gyugyi (2000), DVRs are fast- response power electronic devices capable of injecting missing voltage in series with the power line to restore nominal volt- age levels. They emphasize that DVRs offer a cost-effective alternative to traditional solutions such as capacitor banks and uninterruptible power supplies (UPS). A study by Ghosh and Ledwich (2002) investigates the impact of DVR-based com- pensation on sensitive industrial loads. They found that DVRs significantly reduce downtime and equipment failure caused by voltage fluctuations. Their research also discusses different DVR control strategies, including pre-sag compensation, in- phase compensation, and energy-optimized methods, each with varying degrees of voltage restoration efficiency.

D. Control Strategies for DVR Operation

A Dynamic Voltage Restorer (DVR) is a power electronic device designed to mitigate voltage disturbances such as sags, swells, and transients in power grids. To ensure effective voltage compensation, DVRs rely on advanced control strate- gies that regulate voltage injection, optimize energy usage, and enhance overall system stability. The choice of control strategy significantly impacts the performance of the DVR, influencing response time, accuracy, and efficiency. Various control methods are used in DVRs, including feedforward control, feedback control, proportional-integral (PI) control, fuzzy logic control, and artificial intelligence-based methods. One of the most used approaches is feedforward control, which predicts voltage disturbances in real time and immedi- ately generates a compensation signal. This method enables fast voltage correction by anticipating grid fluctuations rather than reacting to them. However, feedforward control alone may be insufficient for handling complex disturbances that require continuous adjustments. To enhance accuracy, feed-back control is often integrated, where the DVR continuously monitors the output voltage and makes real-time corrections to maintain a stable supply. This combination of feedforward and feedback mechanisms allows DVRs to respond dynamically to changing grid conditions.

Another widely implemented technique is proportional-integral (PI) control, which adjusts the DVR's voltage injection based on deviation from a reference voltage. The proportional component reacts instantly to voltage errors, while the integral component eliminates steady-state errors over time. Despite its effectiveness, PI control may face challenges in handling nonlinear disturbances and requires fine-tuning to prevent oscillations or delays. To improve robustness, fuzzy logic control (FLC) has been introduced, which operates without a predefined mathematical model. Instead, fuzzy logic systems use human-like reasoning to adjust DVR operation based on heuristic rules. This enables faster and more adaptive voltage correction, especially in uncertain or complex grid conditions. With advancements in modern power electronics, artificial intelligence (AI) and machine learning-based control strate- gies are gaining popularity in DVR operation. AI algorithms analyze past voltage disturbances, predict future faults, and optimize DVR response accordingly. These intelligent systems enhance real-time decision-making, allowing DVRs to operate efficiently with minimal human intervention. Neural networks and genetic algorithms are some of the AI techniques used to fine-tune DVR performance, ensuring optimal voltage regula-
tion even in highly dynamic environments.

For high-precision applications, synchronous reference frame (SRF) control is often employed, where the disturbed voltage is transformed into a rotating reference frame to simplify compensation calculations. This technique allows DVRs to accurately inject voltage components in real time, improving the quality of power delivered to sensitive loads. Additionally, space vector pulse width modulation (SVPWM) techniques are used to enhance the efficiency of the inverter system within the DVR, optimizing power conversion and reducing harmonic distortions.

Advantages:

- Fast Response Time: Since this method anticipates volt- age disturbances and compensates instantly, it ensures quick correction of sags and swells.
- Simple Implementation: The control mechanism is straightforward and does not require complex feedback loops, making it easy to design and implement.

Disadvantages:

- Lack of Self-Correction: It does not continuously monitor and adjust for unexpected deviations, which can lead to inaccuracies in voltage restoration.
- Sensitive to Parameter Variations: Any miscalculations or sudden changes in system parameters can lead to ineffective compensation.

E. INFERENCE FROM THE LITERATURE

The literature review on Dynamic Voltage Restorer (DVR) for power quality enhancement highlights key findings in the areas of voltage compensation techniques, control strategies, energy storage methods, and DVR integration in modern power systems. Based on the reviewed studies, several im- portant inferences can be drawn regarding DVR effectiveness, challenges, and future research directions

F. PROPOSED OBJECTIVES

- To Analyze Power Quality Issues in Modern Power Grids
- To Develop and Implement Advanced DVR Control Strategies
- To Evaluate Different Voltage Injection Techniques for Optimal Compensation
- To Optimize Energy Storage Solutions for DVR Opera- tion

III. SURVEY ON VOLTAGE SAG

A voltage sag or voltage dip is a short-duration reduction in the voltage of an electric power distribution system. It can be caused by high current demand such as inrush current (starting of electric motors, transformers, heaters, power supplies) or fault current (overload or short circuit) elsewhere on the system. Voltage sags are defined by their magnitude or depth, and duration. A voltage sag happens when the RMS voltage decreases between 10 and 90 percent of nominal voltage for one-half cycle tone minute .Some references define the duration of a sag for a period of 0.5 cycle to a few seconds, and a longer duration of low voltage would be called a sustained sag. The definition of voltage sag as "A variation of the RMS value of the voltage from nominal voltage for a time greater than 0.5 cycles of the power frequency but less than or equal to 1 minute. Usually further described using a modifier indicating the magnitude of a voltage variation (e.g., sag, swell, or interruption) and possibly a modifier indicating the duration of the variation (e.g., instantaneous, momentary, or temporary)."The main goal of the power system is to provide reliable and high-quality electricity for its customers. One of the main measures of power quality is the voltage magnitude. Therefore, Monitoring the power system to ensure its performance is one of the highest priorities. However, since power systems are usually grids including hundreds of buses, installing measuring instruments at every single busbar of the system is not cost-efficient. In this regard, various approaches have been suggested to estimate the voltage of different buses merely based on the measured voltage on a few buses.

A. CAUSES OF VOLTAGE SAG

1) Short Circuits (Line-to-Ground, Line-to-Line, etc.): These cause a sudden increase in current, leading to a temporary voltage drop.
2) Lightning Strikes: Induces transient faults in overhead power lines, resulting in voltage dips.
3) Equipment or Cable Failures: Faulty transformers, insu- lation breakdown, or cable faults can lead to voltage sags.

4) When large induction motors or synchronous motors start, they draw a high inrush current, which causes a temporary voltage to drop in the network.

5) Common in industrial plants where high-power motors are used for pumps, compressors, conveyors, etc.

6) The connection or disconnection of heavy loads, such as arc furnaces, cranes, or elevators, can cause a significant drop in voltage.

B. SURVEY ON HARMONICS

- Harmonics in power systems are distortions in voltage and current waveforms caused by nonlinear loads. Unlike pure sinusoidal waveforms at the fundamental frequency (50 Hz or 60 Hz), harmonics introduce additional fre- quency components that can degrade power quality. With the increasing integration of power electronic devices, harmonics have become a significant concern in modern electrical networks.
- Harmonic distortion originates from various sources, primarily nonlinear loads such as rectifiers, inverters, variable frequency drives (VFDs), arc furnaces, and electronic equipment. These devices draw current in a non-sinusoidal manner, leading to waveform distortion that propagates throughout the system. The impact of harmonics is observed in increased losses, overheating of transformers and motors, malfunctioning of protective relays, and interference with communication systems.
- Mitigating harmonics involves several techniques, in- cluding the use of passive filters, which absorb specific harmonic frequencies, and active filters, which inject compensating currents to counteract distortions. Phase-shifting transformers help reduce harmonic currents, while improved load design minimizes harmonic gener- ation. In industrial applications, advanced solutions such as Dynamic Voltage Restorers (DVRs) and Flexible AC Transmission Systems (FACTS) contribute to harmonic compensation and voltage stability.
- To regulate harmonics, international standards such as IEEE 519-2014 and IEC 61000 define permissible har- monic levels to ensure power quality compliance. These guidelines establish voltage and current distortion limits for different system voltage levels, helping utilities and industries maintain stable and efficient power networks.

C. SURVEY ON CUSTOMER LOAD PROFILES

Customer load profiles define the variations in power con- sumption patterns across different user categories, includ- ing residential, commercial, and industrial consumers. These profiles influence power system stability and power quality, as fluctuations in demand can cause voltage sags, harmonic distortions, and phase imbalances. Understanding load profiles is essential for maintaining grid reliability and optimizing power quality solutions.

Residential consumers exhibit irregular load patterns, with peak demands occurring in the morning and evening. The use of household appliances such as air conditioners, refrigera- tors, and induction stoves contribute to sudden load changes, leading to voltage fluctuations. Commercial consumers, in- cluding office buildings, malls, and hospitals, typically have a more predictable load profile, with steady energy consump- tion throughout business hours. However, office equipment, HVAC systems, and lighting contribute to harmonic distor- tions. Industrial consumers impose a significant challenge to power quality due to the operation of heavy machinery, large induction motors, and welding equipment, which create volt- age sags, inrush currents, and unbalanced loading conditions. Additionally, the integration of renewable energy sources, such as solar and wind, introduces variability in power generation, contributing to voltage flicker and frequency instability.

D. HEAVY INDUSTRY

Heavy industries, including steel plants, cement factories, mining operations, and large manufacturing units, are among the largest consumers of electrical energy. These industries rely on high-power equipment such as induction motors, arc furnaces, rolling mills, and conveyor systems, which introduce significant power quality issues into the grid. The high inrush currents during motor startups, fluctuating loads, and nonlinear operations cause voltage sags, harmonics, unbalanced loads, and transient disturbances. These issues not only affect the industrial processes but also create instability in the power grid, impacting nearby consumers and utility networks. One of the major power quality concerns in heavy industries is voltage sag, which occurs due to sudden increases in load demand or faults in the distribution system. Voltage sags can disrupt production lines, damage sensitive equipment, and lead to operational downtime. Harmonics generated by variable frequency drives, rectifiers, and welding machines further dis- tort the voltage and current waveforms, increasing losses and reducing system efficiency. Unbalanced loads in three-phase systems cause voltage asymmetry, leading to overheating of motors and transformers, reducing their lifespan..

E. MANUFACTURING INDUSTRY

The manufacturing industry is one of the largest consumers of electrical energy, relying on complex machinery, automation systems, and power electronics for production processes. The use of equipment such as CNC machines, robotic systems, conveyor belts, welding machines, and variable frequency drives introduces significant power quality challenges. These challenges include voltage sags, harmonic distortions, transient disturbances, and unbalanced loads, which can affect pro- duction efficiency, damage sensitive equipment, and increase operational costs.

Voltage sag is a critical issue in manufacturing plants, often caused by sudden load variations, motor startups, and faults in the distribution network. Even short-duration voltage dips can lead to process interruptions, malfunctioning of control systems, and loss of production. Harmonics generated by non- linear loads, such as rectifiers and inverters, lead to waveform distortion, increasing losses in transformers and capacitors.

Additionally, unbalanced loads in three-phase systems create voltage asymmetry, causing overheating of motors and reduc- ing their efficiency and lifespan.

F. COMMERCIAL BUSINESS

Commercial businesses, including office buildings, shopping malls, hospitals, hotels, and data centers, rely heavily on a stable power supply for their daily operations. These establish- ments use a wide range of electrical equipment, such as HVAC systems, lighting, elevators, computers, and communication networks, which contribute to power quality issues. Fluctuat- ing load demands, high penetration of electronic devices, and nonlinear loads generate disturbances such as voltage sags, harmonic distortions, flicker, and unbalanced voltages.

Voltage sag is one of the most common power quality problems in commercial facilities, often caused by sudden load changes, faults in the distribution network, or large equipment switching. Even a brief voltage drop can disrupt critical operations in hospitals, financial institutions, and data centers, leading to system failures and financial losses. Harmonic distortions from electronic devices, such as UPS systems, LED lighting, and variable speed drives, can interfere with sensitive equipment and reduce the efficiency of electrical systems. Unbalanced loads, common in commercial buildings with single-phase and three-phase loads, create voltage imbalances that can stress transformers and electrical networks.

G. SURVEY ON SOURCE OF POWER QUALITY ISSUE

Power quality issues arise from various sources, including faults in the transmission and distribution network, nonlinear loads, renewable energy integration, and unbalanced loads. Voltage sags, harmonic distortions, transients, and flicker are common disturbances affecting the stability and efficiency of electrical systems. Industrial machinery, large motor startups, and power electronic devices contribute significantly to these issues by generating inrush currents and harmonic distortions. To mitigate power quality disturbances, the Dynamic Volt- age Restorer (DVR) is used as a voltage compensation device. It detects voltage sags and injects the necessary voltage in real time to stabilize the power supply. DVRs also help in harmonic filtering, phase balancing, and transient suppression, ensuring reliable operation of sensitive loads in industrial, commercial, and residential sectors.

H. POWER ELECTRONICS

Power electronics play a crucial role in modern power systems by enabling efficient energy conversion, control, and regulation. Devices such as rectifiers, inverters, and converters are widely used in industrial, commercial, and renewable energy applications. However, these nonlinear loads contribute to power quality issues, including voltage sags, harmonic distortions, and transients, which affect system stability and efficiency

I. LOAD SWITCH

Load switching is a common operation in power systems where electrical loads are turned on or off, often causing power quality issues such as voltage sags, transients, and flicker. Industrial processes, large motor startups, and sudden load changes can lead to disturbances that impact sensitive equipment and system stability.

J. SENSITIVE EQUIPMENTS

Sensitive equipment in the power grid, such as control systems, protective relays, communication networks and smart meters, requires a stable and distortion-free power supply for proper operation. Power quality issues like voltage sags, transients, harmonics, and frequency variations can disrupt these systems, leading to faults, mis operations, and even large- scale grid instability.

K. TRANSIENTS

Transients are sudden and short-duration disturbances in electrical circuits that cause an oscillatory response. These disturbances occur due to abrupt changes in voltage or current, lasting for a very short period before the system returns to its normal state. Transients can be caused by external factors like lightning strikes or switching surges, as well as internal factors such as circuit breaker operations, load switching, or faults in the system. Transients can be classified into two main types

1. Impulsive transients:

- These are sharp, sudden changes in voltage or current that occur in one direction, either positive or negative.
- They typically last between 5 microseconds (s) to 50 milliseconds (ms).
- Their characteristics are defined by how quickly they rise, how they decay, and their frequency content.
- Examples include lightning strikes, electrostatic dis- charges, or sudden switching events.

L. 2.Oscillatory Transients:

- These involve rapid fluctuations in voltage or current in both directions (positive and negative).
- They typically last for less than 50 nanoseconds (ns).
- They are described by their magnitude, duration, and frequency spectrum.
- Examples include resonance effects, capacitor switching, or sudden load changes in the power system.

Since transients can damage sensitive equipment and dis- rupt power quality, devices like Dynamic Voltage Restorers (DVRs), surge protectors, and filters are used to mitigate their effects, ensuring grid stability and reliable operation.

IV. STUDY OF DYNAMIC VOLTAGE RESTORER (DVR)

A. Introduction

The increasing demand for high power quality in modern electrical networks has led to the development of advanced compensation devices to mitigate voltage-related disturbances.

Among these devices, the Dynamic Voltage Restorer (DVR) is one of the most effective solutions for addressing voltage sags, swells, and other power quality issues in distribution systems.

B. Dynamic Voltage Restorer (DVR)

A DVR is a power electronics-based device connected in series with the power line to monitor and compensate for voltage fluctuations in real time. It operates by injecting the necessary voltage into the system during disturbances, ensuring a stable and reliable power supply for critical loads. Unlike conventional solutions such as uninterruptible power supplies (UPS) or capacitor banks, DVRs provide a more efficient and dynamic approach to voltage correction.

The study of DVR technology involves understanding its working principle, design, control strategies, and integration with the power grid. Key aspects include its voltage injection methods, energy storage requirements, and response time to different types of disturbances. Additionally, the application of DVRs in industrial, commercial, and renewable energy sectors highlights their role in enhancing overall grid stability and reducing equipment failures due to power quality issues.

C. Basic structures and principles of DVR

The Dynamic Voltage Restorer (DVR) is a series-connected power electronic device designed to mitigate voltage dis- turbances such as sags, swells, and harmonics in power distribution systems. It operates by injecting the necessary compensating voltage into the system to maintain a stable and uninterrupted power supply.

The basic structure of a DVR consists of several key components. A voltage source inverter (VSI) is responsible for generating the compensating voltage by converting DC power into AC. The energy storage system, which may include batteries, capacitors, or other storage technologies, supplies the required energy for voltage compensation. An injection transformer connects the DVR to the distribution line and facilitates the transfer of the compensating voltage. A control unit continuously monitors the power system, detects distur- bances, and regulates the inverter operation to ensure precise compensation. Additionally, a filter circuit helps eliminate switching harmonics and ensures smooth voltage injection.

The DVR operates by continuously monitoring the supply voltage and detecting any deviations from the nominal level. When a voltage disturbance occurs, the control unit calculates the necessary compensation and commands the VSI to gener- ate the required voltage. This voltage is injected in series with the supply through the injection transformer, restoring the load voltage to a stable level. Once the disturbance is mitigated, the DVR returns to its standby state, ready to respond to future fluctuations. By providing fast and efficient voltage compensation, the DVR plays a crucial role in improving power quality and protecting sensitive electrical equipment from voltage-related issues. Its application is essential in industrial, commercial, and renewable energy systems where maintaining a stable power supply is critical.

The basic structure of DVR shown in fig.consists of follow- ing blocks:

- VSI
- Injection transformer
- Passive filter
- Energy storage unit
- Control circuit

A Voltage Source Inverter (VSI) is used in Dynamic Voltage Restorer (DVR) to enhance power quality in the power grid. The VSI in a DVR converts DC power into AC and injects compensating voltage during disturbances such as voltage sags, swells, and harmonics. It operates by generating the missing voltage to restore the nominal load voltage, ensuring a stable and reliable power supply. The VSI-based DVR uses Pulse Width Modulation (PWM) control to achieve fast and precise voltage compensation. It can mitigate power quality issues by dynamically responding to faults, unbalanced loads, and sudden voltage variations in the transmission system. The integration of Split Source Inverter (SSI) in the DVR enhances performance by providing a boosted voltage capability and improved control flexibility, making it more efficient in main- taining power stability

D. Voltage injected by DVR

Voltage injection is a key mechanism used in a Dynamic Voltage Restorer (DVR) to enhance power quality in the power grid. When a disturbance such as a voltage sag, swell, or harmonic distortion occurs, the DVR injects a compensating voltage in series with the grid voltage to maintain a stable load voltage. The injected voltage is generated using a Voltage Source Inverter (VSI), which converts DC power into the required AC voltage.

By dynamically adjusting the injected voltage, the DVR ef- fectively mitigates power quality issues, ensuring that sensitive loads receive a steady and distortion-free voltage supply. The use of advanced control strategies, such as Pulse Width Mod- ulation (PWM) and adaptive reference generation, enhances the DVR's ability to respond quickly to grid disturbances. Incorporating a Split Source Inverter (SSI) in the DVR further improves performance by providing voltage boosting capabil- ity, making the compensation more efficient and reducing the impact of faults on the power system.

E. PASSIVE FILTER

It filters out the harmonics present in the output of the VSI. It can be kept either at the inverter side or at the HV side of the transformer. If filter is placed at the inverter side, switching harmonics are prohibited to enter the injection transformer thereby reduces rating and voltage stress on it. If the filter is placed at HV side of injection transformer, harmonics can enter HV side hence rating of transformer increases

F. ENERGY STORAGE UNIT

During compensation, this unit provide the required real power to generate compensating voltage. Energy storage de- vices are lead acid batteries, flywheels, dc capacitors and super capacitors. Its capacity has great effect on compensation capability of DVR. The system with large disturbance requires real power compensation. DC to AC conversion required for batteries whereas AC to AC conversion required for flywheels

G. CONTROL CIRCUIT

Control circuit steadily observe the system. Its function is to detect any disturbance in the system done by comparing the supply voltage with reference voltage and generate the switch- ing command signals for VSI to generate the compensating voltage by DVR.

V. OPERATION OF DVR WITH SPLIT SOURCE INVERTER

A. MODERN AND TRADITIONAL

Power quality has become a critical concern in modern electrical power systems due to the increasing demand for reliable and stable energy supply. Various disturbances, such as voltage sags, swells, harmonics, flickers, and transients, can significantly impact the performance of industrial and commercial equipment, leading to financial losses and reduced efficiency. To mitigate these issues, Dynamic Voltage Restorers (DVRs) have been widely used as a cost-effective solution for voltage compensation. DVRs are series-connected power devices designed to restore voltage quality by injecting the required compensating voltage into the system whenever dis- turbances occur.

Traditional DVRs commonly utilize Voltage Source Invert- ers (VSIs), which require a separate DC-DC boost converter or large energy storage units to achieve sufficient voltage compensation. However, these systems suffer from higher energy losses, complex circuitry, and bulky components. To overcome these limitations, the integration of a Split Source Inverter (SSI) with a DVR has emerged as an innovative approach. SSI is a single-stage power conversion topology that enables simultaneous voltage boosting and DC-AC con- version, eliminating the need for additional boost converters. This integration enhances DVR efficiency, reduces component count, and improves response time, making it a more effective solution for power quality improvement.

B. OPERATION CONTRAINTS

The Split Source Inverter (SSI)-based DVR operates by detecting voltage disturbances in the power grid and injecting a compensating voltage in real time to maintain a stable supply. The process begins with continuous monitoring of the grid voltage using sensors. When a disturbance such as a voltage sag or swell is detected, the DVR calculates the required compensation and generates the necessary voltage using the SSI.

Unlike conventional VSI-based DVRs, which require a sep- arate DC-DC boost stage, the SSI inherently provides voltage boosting within the inverter topology itself, simplifying the system design. The DC power source (battery, supercapacitor, or renewable energy system) supplies energy to the SSI, which converts it directly into AC voltage at the desired magnitude and phase angle. Through Pulse Width Modulation (PWM) techniques, the DVR injects the compensating voltage in series with the supply line, ensuring that the load voltage remains within acceptable limits.

The control system plays a crucial role in the operation of the DVR. Advanced control algorithms such as Fuzzy Logic Control (FLC), Artificial Intelligence (AI)-based control, and Space Vector Pulse Width Modulation (SVPWM) enable real- time adjustment of the injected voltage, ensuring optimal com- pensation with minimal energy consumption. These intelligent control methods allow faster response times, reduced harmonic distortion, and improved stability, making the SSI-based DVR a superior alternative to traditional compensation methods.

C. SPWM TECHNIQUE

SPWM is a modulation technique that controls the inverter within the DVR to generate a smooth, sinusoidal output voltage. It is achieved by comparing a reference sinusoidal signal with a high-frequency triangular carrier signal. The intersection points determine the switching instants of the inverter, creating a pulse train that approximates a sinusoidal waveform. The key advantages of SPWM in power quality applications include: - Reduction of Harmonic Distortion: SPWM minimizes Total Harmonic Distortion (THD), ensuring that the injected compensating voltage does not introduce additional distortions into the grid. - Efficient Voltage Com- pensation: The DVR must respond quickly to disturbances, and SPWM enables smooth and precise voltage injection, ensuring that load voltage remains stable. - Improved Power Conversion Efficiency: By effectively switching the inverter's power devices, SPWM reduces switching losses and enhances overall system efficiency.

1. Modeling the Power Grid and Load: A three-phase power system with a transmission line and load is created.
2. Introducing Fault Conditions: Voltage sag and swell con- ditions are simulated by introducing faults in the transmission line.
3. Designing the DVR System: The DVR is modeled with a three-phase inverter, using an SPWM switching control scheme.
4. Injecting Compensating Voltage: The DVR detects dis- turbances and injects voltage using the SPWM-controlled inverter.
5. Analyzing Power Quality Improvement: The load voltage is monitored to evaluate how effectively the DVR restores normal operating conditions.

D. 4.4 SPWM TECHNIQUE AND FORMULAS

In the SVPWM scheme for a Split Source Inverter (SSI), the inductor LLL is charged with a duty cycle D, given by D= ty/(t.x+ t y D), where t.x t.x t x and t y are switching time intervals Considering the modulation index M definition and based on the duty cycle D is related to M by:

The duty cycle D is not constant, as it varies with a low frequency equals to six times the fundamental frequency. This variation is higher in the case of the sinusoidal pulse width modulation (SPWM) scheme, where D varies with a low frequency equals to three times the fundamental frequency with higher amplitude. The duty cycle variation of the SVPWM is bounded by the inductor is charged with an average duty cycle Dav shown in fig. 2

The duty cycle variation of the SVPWM is bounded by the inductor is charged with an average duty cycle Dav given by Based on the inductor flux balance and the capacitor charge balance, the normalized average inverter voltage V Vinv DC

is given by

The normalized output fundamental peak phase voltage V 1 /DC is

Finally, the selection of the inductor should consider the high-frequency and the low-frequency current components due to the switching and the duty cycle variation, respectively. This is done by finding a high frequency ripple for the inductor current ILh and the capacitor voltage V invh given by

Under worst conditions, the low frequency ripple is added to the high frequency one; thus, the required inductance and capacitance are given by

where, $\triangle IL = \triangle IL_l + \triangle IL_h$ and $\triangle V_{inv} = \triangle V_{inv_l} + \triangle V_{inv_h}$.

E. Other PWM Schemes

The mathematical equations for the SPWM, the THPWM, and the BTHPWM modulation schemes are introduced in this subsection, where the duty cycle (D) and its average value (Dav) of each modulation of these modulation schemes can be determined by

where 7/6pi 11pi/6 and M is modulation index Meanwhile, the normalized inverter and output fundamental peak phase voltages can be determined by

Finally, the inductor and the capacitor values can be calculated considering the same steps as before. The result is

where, K is a constant given by

Dmin, and Dmax are minimum and maximum values of the duty cycle given by

Note that, the low frequency ripple components in the case of the THPWM and the BTHPWM schemes have been calculated considering the lowest two harmonics of the Fourier series of (15) because they have comparable amplitudes. As a worst condition, the two harmonic amplitudes have been simply summed together and they yield the two terms in the K definition of (21). It worth noting that the low frequency component using the SPWM scheme is very high compared to the SVPWM due to two main reasons: the first one is the order of the low frequency component, which is six times the fundamental component using the SVPWM scheme and three times the fundamental component using the SPWM scheme, while the second reason is the lower duty cycle variations for the SVPWM scheme, which results in a lower low frequency component amplitude. The ratio between the low frequency component in the inductor current using the SPWM scheme and its equivalent using the SVPWM scheme can be calculated from the low frequency terms in (13) and (19) to be 7.58. The same ratio exist for the low frequency component in the inverter voltage neglecting the high frequency term.

F. Modified SVPWM Scheme

The low frequency component in the inductor current and the inverter voltage using the aforementioned modulation schemes is important. This low frequency component can be eliminated by fixing the duty cycle D. This can be done by recalling the switching pattern of the SVPWM scheme during any sector where Ts is the sampling time, Ta and Tb are the sector two equivalent active states times, and Tz is the zero states equivalent time. Hence, redistributing the zero states equivalent time without affecting the active states time is the key point. The discharging time tx of the inductor L is fixed to the minimum value of the zero state equivalent time Tzm, given by

During any sector where the remaining zero states time is assigned to the other zero state. By making tx = Tzm, the biasing, discussed before, is automatically achieved where the reference signals using this modification are shows that the lower virtual envelop is constant, where the duty cycle D is now fixed and equal to M.The normalized inverter and output fundamental peak phase voltages can now be calculated by

Finally, the inductor and capacitor values can be calculated, as in the boost converter, by considering only the switching frequency ripple given by (8) and (9) with D = M, i.e.:

G. Advantages of DVR with Split Source Inverter

The integration of Split Source Inverter (SSI) into a DVR offers several benefits compared to conventional VSI-based DVR systems:

- Single-Stage Power Conversion: Unlike traditional DVRs that require a separate DC-DC boost converter, the SSI provides inherent voltage boosting, simplifying the system, and reducing component count.
- Higher Efficiency: By eliminating multiple conversion stages, energy losses are minimized, leading to improved overall system efficiency.
- Faster Response Time: The single-stage structure of the SSI allows instantaneous compensation of voltage disturbances, ensuring minimal impact on sensitive loads.
- Reduced System Complexity and Cost: The need for large energy storage devices, additional converters, and extensive circuitry is significantly reduced, lowering the overall cost and size of the DVR system.
- Better Performance in Renewable Energy Systems: The SSI-based DVR can efficiently regulate voltage fluctuations caused by solar and wind energy integration, improving the stability of power supply in renewable- based grids.
- Improved Harmonic Reduction: Advanced PWM tech- niques reduce the harmonic distortion introduced during voltage compensation, leading to better power quality.

Disadvantages of DVR with Split Source Inverter Despite its numerous advantages, the SSI-based DVR also has certain limitations:

- Limited Voltage Boosting Capability: Although the SSI provides voltage boosting, the boost ratio is lower com- pared to dedicated DC-DC converters, which may limit its effectiveness in handling extreme voltage sags.
- Complex Control Strategy: The operation of an SSI-based DVR requires sophisticated control algorithms, which increase computational complexity and demand higher processing power.
- Dependency on DC Power Source: The performance of the DVR is influenced by the availability and stability of the DC energy source, such as batteries or supercapaci- tors, which may require frequent maintenance.

VI. SIMULATION)

A. WORKING OF SIMULATION

In the MATLAB simulation, the three-phase Split Source Inverter (SSI) is a key component of the Dynamic Voltage Re- storer (DVR), responsible for injecting compensating voltage into the power grid when a fault occurs. The SSI operates as a single-stage DC-AC converter with inherent voltage boost- ing, allowing it to supply the required compensation voltage directly from the energy storage system without the need for a separate DC-DC boost converter. This design improves system efficiency, reduces component count, and enhances the DVR's dynamic response to voltage disturbances.

When a fault is introduced in the transmission line, the voltage across the system experiences a drop due to the increased current flow and impedance variations. The DVR, which continuously monitors the voltage levels, detects this real-time drop, and immediately activates the compensation mechanism. The SSI-based voltage source inverter plays a critical role at this stage by converting the DC power from the energy storage system into an AC voltage that matches the missing portion of the supply voltage. This injected voltage is then fed into the system through a series transformer, ensuring that the load receives a stable and undistorted power supply.

The operation of the SSI in this process is based on its unique topology, which allows simultaneous voltage boosting and DC-AC conversion. Unlike conventional Voltage Source Inverters (VSIs), which require a separate step-up converter to raise the DC voltage before inversion, the SSI achieves this in a single stage using a split inductor and a modified switching sequence. During normal operation, the inverter functions like a typical VSI, delivering power as required. However, when a voltage sag is detected, the SSI increases its output voltage by utilizing the stored energy efficiently, ensuring that the compensating voltage is sufficient to counteract the disturbance.

The control strategy of the SSI-based DVR plays a crucial role in ensuring a smooth and accurate response. Using advanced control techniques such as Space Vector Pulse Width Modulation (SVPWM) or hysteresis control, the inverter reg- ulates the magnitude, phase, and frequency of the injected voltage. This ensures that the compensation is both precise and adaptive, adjusting dynamically to varying fault conditions.

The fast response time of the SSI, combined with its inherent boost capability, allows for seamless mitigation of voltage sags and swells, preventing damage to sensitive loads connected to the system.

Overall, the three-phase Split Source Inverter enhances the DVR's ability to stabilize power quality in the presence of grid disturbances. By eliminating the need for a separate boost converter, it reduces energy losses, improves system efficiency, and enables a compact and cost-effective solution for power quality improvement. The simulation results in MATLAB demonstrate how the SSI-based DVR effectively compensates for voltage drops, ensuring uninterrupted and high-quality power delivery to the load.

B. CALCULATIONS

Vdc	100V
Idc	20A
VΦ1	$110\sqrt{2}$V
pf	0.8 lag
I Φ1	$7.58\sqrt{2}$A
fs	10.0 kHz
f1	50 Hz

M	V_{inv} (V)	D_{min}	D_{max}	L (mH)	C (μF)
0.6804	457	0.6701	0.7946	3.1	86.6

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REFERENCES

[1] F. Z. Peng, "Z-source inverter," IEEE Transactions on Industry Applications, vol. 39, no. 2, pp. 504–510, Mar 2003.

[2] Y. Siwakoti, F. Z. Peng, F. Blaabjerg, P. C. Loh, and G. Town, CDSP "Impedance-source networks for electric power

conversion part i: A topological review," IEEE Transactions on Power Electronics, vol. 30, no. 2, pp. 699–716, Feb 2015.
[3] L. Zhang, D. Xu, G. Shen, M. Chen, A. Ioinovici, and X. Wu, "A high step-up dc to dc converter under alternating phase shift control for fuel cell power system," Power Electronics, IEEE Transactions on, vol. 30, no. 3, pp. 1694–1703, March 2015.
[4] V. Samavatian and A. Radan, "A high efficiency in- put/output magnetically coupled interleaved buck-boost con- verter with low internal oscillation for fuel-cell applications: Ccm steady-state analysis," IEEE Transactions on Industrial Electronics, vol. 62, no. 9, pp. 5560–5568, Sept 2015.
[5] P. Cossutta, M. Aguirre, A. Cao, S. Raffo, and M. Valla, "Single stage fuel cell to grid interface with multilevel current- source inverters," Industrial Electronics, IEEE Transactions on, vol. 62, no. 8, pp. 5256 5264, Aug 2015.
[6] M.-K. Nguyen, Y.-C. Lim, and S.-J. Park, "A comparison between single-phase quasi- z-source and quasi-switched boost inverters," Industrial Electronics, IEEE Transactions on, vol. 62, no. 10, pp. 6336–6344, Oct 2015.
[7] J. Cai and Q.-C. Zhong, "An asymmetrical z-source hybrid power converter with space vector pulse-width modula- tion," in Energy Conversion Congress and Exposition (ECCE), 2014 IEEE, Sept 2014, pp. 344–349.
[8] M. Mohr, W. Franke, B. Wittig, and F. Fuchs, "Converter systems for fuel cells in the medium power range;a compara- tive study," IEEE Transactions on Industrial Electronics, vol. 57, no. 6, pp. 2024–2032, June 2010.
[9] A. Hakeem, A. Elserougi, A. El Zawawi, S. Ahmed, and A. Massoud, "A modified capacitor voltage control al- gorithm for suppressing the effect of measurement noise on grid-connected z-source inverters controllers," in Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE, Nov 2013, pp. 204–209.
[10] A. Abdelhakim, "Analysis and modulation of the buck-boost voltage source inverter (bbvsi) for lower voltage stresses," in Industrial Tech nology (ICIT), 2015 IEEE International Conference on, March 2015, pp. 926–934.