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Power Quality Improvement in Distribution Networks under High Renewable Energy Penetration

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Abstract

The rapid integration of renewable energy sources such as solar photovoltaic (PV) and wind power into distribution networks has significantly transformed modern power systems. While renewable energy enhances sustainability and reduces carbon emissions, high penetration levels introduce various power quality challenges including voltage fluctuations, harmonic distortion, reverse power flow, and frequency instability. These disturbances affect system reliability, equipment performance, and consumer satisfaction. This paper presents a comprehensive study on power quality issues arising from large-scale renewable integration and proposes effective mitigation techniques. Advanced control strategies such as smart inverter-based Volt-VAR and Volt-Watt control, distribution static compensators (DSTATCOM), active power filters, and energy storage systems are analyzed for improving voltage profile and harmonic performance. Simulation-based validation demonstrates that coordinated control of distributed energy resources can significantly enhance power quality and maintain network stability under high renewable penetration scenarios.

Keywords: Renewable Energy Integration, Power Quality, Distribution Network, Voltage Regulation, Harmonics, DSTATCOM, Smart Inverters, Energy Storage Systems.

INTRODUCTION

The accelerating shift toward sustainable and low-carbon energy systems has significantly increased the integration of renewable energy resources into electrical distribution networks. Among these resources, solar photovoltaic (PV) systems and wind turbines are the most widely deployed due to their environmental benefits and decreasing installation costs. Unlike traditional power systems that rely on centralized generation from thermal or hydroelectric plants, modern distribution networks now accommodate a large number of decentralized generation units connected close to the load centers. Conventional distribution systems were originally designed to operate with a unidirectional power flow—from centralized generation stations through transmission networks to end consumers. However, with the widespread adoption of rooftop solar panels, community solar farms, and small-scale wind installations, power flow has become bidirectional. During periods of high renewable generation and low local demand, excess power is injected back into the upstream network. This structural change challenges the operational philosophy, protection schemes, and voltage .One of the primary technical concerns associated with high renewable penetration is voltage regulation. Solar PV output fluctuates with changes in solar irradiance due to passing clouds, seasonal variation, and temperature effects. Similarly, wind power output depends heavily on wind speed variability. These fluctuations can result in rapid voltage rise or voltage drop at different points along the feeder. When generation exceeds local consumption, voltage levels may exceed statutory limits, potentially damaging sensitive equipment. Conversely, sudden reduction in renewable output may cause voltage sag and affect power reliability.

Another critical issue is harmonic distortion introduced by power electronic converters. Renewable energy systems interface with the grid through inverters and converters, which switch at high frequencies to convert DC power into AC. Although modern inverters are designed with harmonic filtering capabilities, large-scale integration of multiple units can collectively increase Total Harmonic Distortion (THD) in the system. Elevated harmonic levels may cause overheating of transformers, malfunction of protection devices, and reduced lifespan of electrical equipment. High penetration of inverter-based generation also reduces the overall inertia of the power system. Conventional synchronous generators naturally provide mechanical inertia that helps maintain frequency stability during sudden load or generation changes. In contrast, most renewable systems are connected through power electronic interfaces that do not inherently contribute to system inertia. As a result, frequency deviations may occur more rapidly in renewable-dominated systems, increasing the risk of instability.

Furthermore, reverse power flow can disturb conventional protection coordination. Protection devices such as overcurrent relays and reclosers were designed assuming fault currents flow in one direction. With distributed generation injecting power locally, fault current magnitude and direction may vary, complicating fault detection and isolation. This necessitates adaptive protection schemes and intelligent control mechanisms.

Power quality, therefore, becomes a multi-dimensional concern encompassing voltage magnitude stability, frequency regulation, harmonic performance, voltage imbalance, and flicker mitigation. Maintaining these parameters within permissible standards defined by grid codes and regulatory bodies is essential for ensuring reliable operation of both utility infrastructure and consumer equipment.

To address these emerging challenges, advanced control strategies and compensation techniques are required. Smart inverters capable of reactive power control, dynamic voltage regulation devices such as Distribution Static Compensators (DSTATCOM), active power filters, on-load tap changers (OLTC), and battery energy storage systems play a significant role in enhancing system performance. In addition, real-time monitoring using smart meters and supervisory control systems enables better visibility and adaptive response to network disturbances.

Therefore, improving power quality in distribution networks with high renewable energy penetration is not merely a technical enhancement but a necessary evolution of grid infrastructure. Developing intelligent, flexible, and resilient distribution systems is essential to support the continued growth of renewable energy while maintaining stability, reliability, and compliance with power quality standards.

LITERATURE REVIEW

Extensive research has been conducted to analyze the influence of renewable energy integration on the operational performance of distribution systems. As distributed generation becomes more widespread, researchers have focused on understanding its impact on voltage stability, harmonic performance, feeder loading, and protection coordination.

A significant number of studies report that high rooftop solar PV penetration in low-voltage distribution feeders often results in voltage rise, particularly during midday hours when solar irradiance is at its peak and local load demand is relatively low. This condition is more severe in rural or weak networks with high feeder impedance. Researchers have demonstrated that conventional voltage regulation devices, such as capacitor banks and on-load tap changers, may not respond quickly enough to fast solar fluctuations. Consequently, smart inverter-based reactive power control has emerged as an effective mitigation strategy. By dynamically injecting or absorbing reactive power, inverters can regulate local voltage and reduce the likelihood of overvoltage conditions without requiring additional hardware installation.

In addition to voltage issues, harmonic distortion caused by inverter-interfaced renewable sources has been widely studied. Although individual inverters are designed to comply with harmonic standards, the aggregated effect of multiple distributed units connected across a feeder may increase Total Harmonic Distortion (THD). Research indicates that resonance between feeder impedance and inverter switching frequencies can amplify certain harmonic components. Studies further emphasize that harmonic distortion not only affects power quality but also increases losses and thermal stress in transformers and cables. To address this, active filtering techniques and improved inverter switching algorithms have been proposed.

Voltage flicker and rapid voltage fluctuations due to intermittent renewable output have also been investigated. Wind farms, in particular, may introduce short-term voltage variations due to turbulent wind conditions. Several researchers suggest that advanced control schemes incorporating real-time monitoring and adaptive reactive power compensation can effectively minimize flicker levels.

The application of Flexible AC Transmission System (FACTS) devices in distribution networks has gained considerable attention. Among these, the Distribution Static Compensator (DSTATCOM) is frequently analyzed for its capability to provide fast-acting reactive power support. Studies demonstrate that DSTATCOM can effectively mitigate voltage sag, swell, imbalance, and harmonics. Its performance is particularly beneficial in feeders with high renewable penetration where voltage deviations occur frequently. Compared to conventional capacitor banks, DSTATCOM offers superior dynamic response and continuous control.

Energy Storage Systems (ESS) have emerged as another promising solution to address renewable intermittency. Research findings show that battery energy storage can absorb surplus energy during high generation periods and supply power during sudden generation drops. This buffering capability reduces voltage fluctuations and enhances frequency stability. Moreover, ESS can support peak load management and improve feeder hosting capacity. However, economic considerations and optimal sizing of storage systems remain active areas of research.

Several studies have also explored the concept of coordinated or hierarchical control strategies. Instead of operating compensation devices independently, integrated control approaches allow smart inverters, DSTATCOM, voltage regulators, and storage units to function cooperatively. Such coordination improves overall system efficiency and prevents control conflicts. Recent advancements include decentralized and distributed control architectures that enhance scalability in large networks with numerous distributed energy resources.

Furthermore, grid codes and standards such as IEEE 519 and IEEE 1547 have been analyzed in the context of renewable integration. Researchers emphasize that compliance with harmonic limits, voltage ride-through requirements, and reactive power support capabilities is essential for maintaining grid reliability. Modern inverter standards now require features such as low-voltage ride-through (LVRT) and grid-support functions, reflecting the evolving role of distributed generators from passive energy sources to active grid participants

METHODOLOGY

1. System Modeling: A distribution feeder integrated with solar PV systems is modeled to analyze the impact of high renewable penetration on power quality parameters.
2. Power Quality Monitoring: Voltage magnitude, frequency, reactive power, and Total Harmonic Distortion (THD) are continuously observed to detect disturbances such as voltage rise, sag, and harmonics.
3. Smart Inverter Control: Volt-VAR and Volt-Watt control strategies are implemented in renewable inverters to regulate voltage and limit overvoltage conditions.
4. Reactive Power Compensation: A DSTATCOM is integrated to provide dynamic reactive power support and improve voltage stability.
5. Energy Storage Support: A battery energy storage system is used to absorb excess power and supply power during fluctuations to maintain system stability.

EXISTING SYSTEM

The conventional distribution network is primarily designed for unidirectional power flow from centralized generation stations to end consumers. Voltage regulation is mainly achieved using devices such as capacitor banks, on-load tap changers (OLTC), and voltage regulators.

With the increasing integration of renewable energy sources like solar PV and wind systems, these traditional systems face operational challenges. The existing system mainly focuses on basic monitoring and does not provide dynamic control to handle rapid voltage fluctuations, reverse power flow, or harmonic distortion caused by inverter-based generation.

Conventional compensation methods are slow in response and not fully suitable for high renewable penetration levels. As a result, issues such as voltage rise, voltage sag, frequency variation, and increased Total Harmonic Distortion (THD) may occur, affecting overall power quality and system reliability.

The traditional distribution network is designed to operate with centralized power generation and unidirectional power flow from generating stations to consumers. Voltage regulation is typically maintained using conventional devices such as on-load tap changers (OLTC), capacitor banks, and voltage regulators installed at substations. These devices are generally slow-acting and operate based on preset settings rather than real-time system conditions.

In the existing system, renewable energy sources such as solar PV and wind turbines are connected without advanced coordinated control strategies. Although grid-connected inverters comply with basic standards, their operation is often limited to delivering active power without actively supporting voltage or reactive power regulation.

With increasing renewable penetration, conventional networks experience several limitations. During peak solar generation and low load demand, voltage rise may occur at the end of feeders due to excess power injection. Similarly, sudden reduction in renewable output can lead to voltage dips and instability.

Another limitation of the existing system is inadequate harmonic management. Multiple inverter-based renewable units can introduce harmonic distortion into the network. Traditional systems rely mainly on passive filtering or standard compliance, which may not be sufficient under high penetration levels.

Reverse power flow is another challenge in the existing setup. Protection schemes such as overcurrent relays and fuses are designed assuming forward power flow. When power flows back toward the substation due to distributed generation, protection coordination may become unreliable.

Overall, the conventional distribution system lacks intelligent monitoring, dynamic reactive power support, coordinated control mechanisms, and energy storage integration. These limitations reduce the ability of the existing system to maintain acceptable power quality under high renewable energy penetration.

PROPOSED SYSTEM

The proposed system presents an integrated approach for improving power quality in distribution networks with high renewable energy penetration. Unlike conventional systems that rely only on passive voltage regulation devices, the proposed framework incorporates intelligent control strategies and dynamic compensation techniques. The system consists of a distribution feeder connected with multiple solar PV units operating under high penetration conditions. Each PV unit is interfaced through smart inverters capable of providing both active and reactive power control. strategies to regulate voltage and prevent overvoltage during peak generation periods.

To enhance voltage stability, a Distribution Static Compensator (DSTATCOM) is installed at a suitable bus location. The DSTATCOM provides fast reactive power injection or absorption based on real-time voltage measurements, thereby mitigating voltage sag and swell conditions.

A Battery Energy Storage System (BESS) is integrated into the network to manage renewable intermittency. The storage system absorbs excess power during high generation and supplies power during sudden generation drops, maintaining voltage and frequency stability.

A coordinated control mechanism continuously monitors system parameters such as voltage, frequency, and harmonic distortion. Based on these measurements, the controller dispatches appropriate control signals to smart inverters, DSTATCOM, and energy storage units to maintain power quality within permissible limits.

The proposed system ensures improved voltage profile, reduced harmonic distortion, enhanced system reliability, and better stability under high renewable energy penetration conditions.

A coordinated supervisory control monitors voltage, current, and harmonic levels across the network. Based on this information, control signals are dispatched to inverters, DSTATCOM, and BESS to optimize power quality and maintain grid stability.

Battery Energy Storage Systems (BESS) are included to smooth renewable output variations. By storing excess energy during high generation periods and injecting power during deficits, the system ensures reliable voltage and frequency regulation.

BLOCK DIAGRAM

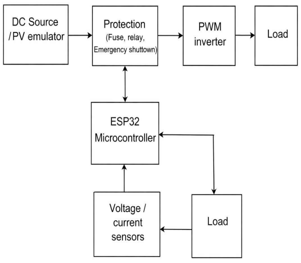

Fig 1-Block Diagram

SYSTEM DESIGN

The proposed power conversion and monitoring system is designed to convert DC power obtained from a photovoltaic (PV) source into stable and

regulated AC power while ensuring safety, reliability, and improved power quality. The system integrates power conversion, protection, sensing, filtering, and intelligent control into a single coordinated framework. The overall architecture consists of five major subsystems: the DC input stage, protection stage, inverter stage, control and
monitoring unit, and output filtering and load interface stage. Each subsystem performs a specific function and collectively ensures efficient and stable operation.

The DC input stage consists of a PV emulator or DC power source that simulates the electrical characteristics of a solar panel. This stage provides variable DC voltage depending on operating conditions, allowing the system to replicate real-world renewable energy behavior. Proper voltage regulation at this stage ensures that the inverter receives a stable input supply.

The protection stage is implemented to safeguard the system against abnormal operating conditions such as overcurrent, short circuit, and voltage surges. This stage includes protective components such as fuses, Transient Voltage Suppression (TVS) diodes, and an emergency stop switch. The fuse protects against excessive current flow, while the TVS diode suppresses sudden voltage spikes.

The inverter stage forms the core of the system. A PWM (Pulse Width Modulation) inverter is used to convert DC power into AC power. High-frequency switching devices such as MOSFETs or IGBTs are controlled using PWM signals to generate the desired AC waveform.

The sensing unit consists of voltage and current sensors placed at the inverter output. These sensors provide real-time feedback signals to the microcontroller. The feedback mechanism enables closed-loop control, which improves voltage regulation accuracy and ensures stable operation under varying load conditions.

The output filtering stage includes an LC filter connected at the inverter output. Since the PWM inverter produces high-frequency switching harmonics, the LC filter smooths the waveform and reduces. The inductor limits current ripple, while the capacitor filters voltage ripple, resulting in a near-sinusoidal AC output suitable for sensitive loads.

Top of Form

Bottom of Form

Finally, the load interface stage delivers the filtered AC power to the connected load. The system is designed to maintain stable voltage and frequency even when the load varies. Through coordinated control between sensing, processing, and switching, the system ensures reliable power delivery with improved efficiency and reduced distortion.

To improve system dynamic response, a closed-loop voltage control strategy is implemented within the microcontroller. The sensed output voltage is continuously compared with a reference value, and the error signal is processed to adjust the PWM duty cycle. This regulation mechanism ensures fast correction during sudden load variations and maintains a constant output voltage. As a result, the system achieves improved stability and reduced steady-state error.

The design also emphasizes efficient power conversion by minimizing switching and conduction losses in the inverter stage. Proper selection of switching frequency and semiconductor devices enhances overall efficiency. Heat dissipation mechanisms such as heat sinks are incorporated to maintain safe operating temperature. This ensures reliable long-term operation under continuous load conditions.

In addition, harmonic mitigation is considered as a key design objective. The LC filter parameters are carefully selected to suppress high-frequency switching components without affecting the fundamental frequency. This reduces Total Harmonic Distortion (THD) and improves waveform quality. Consequently, the output becomes suitable for both resistive and sensitive electronic loads.

The system architecture also allows future integration with renewable energy and smart grid applications. Communication interfaces can be added for remote monitoring and data logging. This enables performance tracking, fault diagnosis, and predictive maintenance. The modular and scalable design makes the system adaptable for advanced power quality improvement applications.

Overall, the proposed system design emphasizes safety, intelligent control, harmonic reduction, and stable DC-to-AC power conversion. The integration of protection mechanisms, real-time monitoring.

HARDWARE MODEL

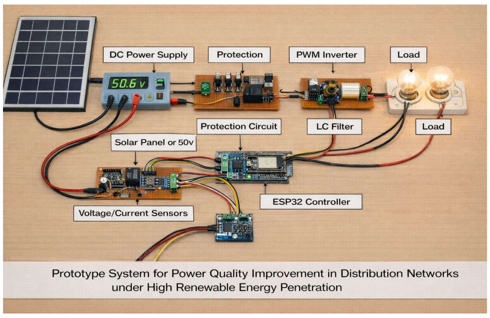

Fig 2- Prototype

CONCLUSIONS

This work presented the design, modeling, and simulation of a PWM-based inverter system integrated with closed-loop control for enhanced power conversion and improved power quality performance. The proposed system was developed to efficiently convert DC power from a photovoltaic (PV) source into regulated AC power while ensuring waveform quality, voltage stability, and system reliability. The overall architecture combines protection mechanisms, intelligent control using an ESP32 microcontroller, sensing and feedback units, and an LC output filter to achieve stable and efficient operation.

The MATLAB/Simulink model was used to analyze system behavior under varying input voltage and load conditions. The simulation results demonstrated that the inverter successfully converts DC input into AC output using SPWM control. Although the raw inverter output contains switching harmonics, the inclusion of the LC filter effectively reduces high-frequency components and produces a near-sinusoidal waveform. Harmonic analysis confirmed a significant reduction in Total Harmonic Distortion (THD), indicating improved power quality suitable for practical applications.

The closed-loop control mechanism played a crucial role in maintaining output voltage regulation. During sudden load variations, minor transient deviations were observed; however, the controller quickly adjusted the PWM duty cycle and restored the voltage to its reference value within a short settling time. This confirms that the system exhibits good dynamic response and stable performance under real operating conditions.

In addition to improved waveform quality and voltage regulation, the system design ensures enhanced safety and reliability through protective components such as fuses, surge protection devices, and controlled shutdown mechanisms.

The modular architecture allows easy integration with renewable energy systems and potential expansion for smart monitoring or IoT-based supervision.

Overall, the proposed inverter system provides an effective and reliable solution for renewable energy–based power conversion. The combination of intelligent control, harmonic mitigation, and efficient filtering improves overall system performance and ensures stable, high-quality AC power delivery. The simulation results validate the effectiveness of the proposed design and confirm its suitability for practical implementation in distributed energy and power quality improvement applications.

FUTURE SCOPE

The proposed inverter-based power conversion and power quality improvement system can be further enhanced by integrating advanced grid synchronization techniques. By incorporating phase-locked loop (PLL) control and anti-islanding protection, the system can be extended for safe grid-connected applications. This would enable seamless integration with utility networks and improve overall grid stability

The implementation of advanced modulation techniques such as Space Vector PWM (SVPWM) or adaptive control algorithms can further reduce harmonic distortion and improve voltage regulation. Intelligent controllers such as AI-based or predictive control methods can also be incorporated to optimize switching performance and enhance dynamic response under varying load conditions.

The system can be expanded into a three-phase configuration to support industrial and high-power applications. A multi-inverter architecture with coordinated control can improve power handling capacity and provide better power quality performance in distributed energy systems.

Integration of IoT-based monitoring and data logging features can allow remote supervision of voltage, current, power, and THD levels. This would enable real-time performance analysis, fault detection, and predictive maintenance, making the system suitable for smart grid and renewable energy applications.

Future improvements may also include the addition of active power filters or hybrid filtering techniques to further minimize harmonic distortion and improve overall efficiency. This enhancement would make the system more suitable for sensitive loads and high-performance power quality applications.

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