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Power Quality Improvement in Solar-Integrated Electric Vehicle Charging Stations Using Unified Power Quality Conditioner (UPQC)

DEBANJAN ROY[1], PRASHANT KUMAR[2]
[1, 2] Faculty of Engineering, Teerthankar Mahaveer University, Moradabad

Abstract- The rapid growth of electric vehicles (EVs) and renewable energy integration has significantly transformed modern power systems. Solar photovoltaic (PV) based EV charging infrastructure has emerged as an environmentally sustainable solution for transportation electrification. However, the integration of solar generation and EV charging loads introduces several power quality issues such as voltage fluctuations, harmonic distortion, reactive power imbalance, and load instability. These disturbances arise primarily due to the use of power electronic converters and the intermittent nature of solar energy generation. Poor power quality may lead to reduced efficiency of electrical equipment, overheating of devices, malfunction of protection systems, and instability in distribution networks. Therefore, improving power quality in solar-integrated EV charging stations is essential for ensuring reliable and efficient operation of the electrical grid. This research investigates the application of a Unified Power Quality Conditioner (UPQC) for mitigating power quality issues in solar-integrated EV charging systems. The UPQC is a custom power device consisting of series and shunt active power filters that operate simultaneously to compensate voltage and current disturbances. In the proposed system, a solar photovoltaic array is connected to a grid-integrated EV charging station through power electronic converters. The UPQC is installed at the point of common coupling (PCC) to regulate voltage variations, suppress current harmonics, and improve the power factor. The proposed model is implemented using simulation tools to analyze system performance under different operating conditions. Key parameters such as Total Harmonic Distortion (THD), voltage sag/swell, reactive power compensation, and load stability are evaluated. Simulation results demonstrate that the UPQC effectively reduces current harmonics, stabilizes voltage profiles, and improves overall system efficiency. The integration of UPQC also ensures compliance with power quality standards and enhances the reliability of solar-powered EV charging infrastructure. The findings of this study highlight the potential of UPQC-based compensation techniques in addressing the growing power quality challenges associated with renewable energy-based EV charging stations.

Keywords: Electric Vehicles, Solar Photovoltaic, Power Quality Improvement, Unified Power Quality Conditioner, EV Charging Station

I. INTRODUCTION

The global transition toward sustainable energy and transportation has accelerated the adoption of electric vehicles (EVs) and renewable energy technologies such as solar photovoltaic (PV) systems [1]. Electric vehicles are widely recognized as a promising solution for reducing greenhouse gas emissions and dependence on fossil fuels [2]. As EV adoption increases, the development of efficient charging infrastructure has become a critical component of modern power systems [3].

Solar energy has emerged as one of the most attractive renewable energy sources for powering EV charging stations due to its abundance and environmental benefits [4]. Integrating solar PV systems with EV charging infrastructure can reduce grid dependency and enable clean transportation solutions [5]. However, the combination of solar generation and EV charging loads introduces several operational challenges related to power quality [6].

Power quality refers to maintaining stable voltage, frequency, and waveform characteristics within acceptable limits for reliable power system operation [7]. In solar-integrated EV charging stations, various disturbances such as voltage sag, voltage swell, harmonics, and reactive power imbalance frequently occur due to the presence of power electronic converters and nonlinear loads [8]. These disturbances can degrade system performance and affect both the grid and connected loads [9].

The power electronic converters used in EV chargers generate harmonic currents that distort the supply waveform and reduce power quality [10]. Similarly, solar PV systems rely on inverters for grid integration, which may also introduce switching harmonics and voltage fluctuations [11]. As a result, the integration of EV chargers and renewable energy sources increases the complexity of power system operation [12].

Another challenge arises from the intermittent nature of solar energy generation. Variations in solar irradiation lead to fluctuations in output power, causing voltage instability and power imbalance in distribution networks [13]. These fluctuations can affect the stability of EV charging stations and may lead to increased losses in electrical equipment [14].

To address these issues, several power quality improvement techniques have been proposed, including passive filters, active power filters, and custom power devices [15]. Among these solutions, the Unified Power Quality Conditioner (UPQC) has gained significant attention due to its capability to simultaneously mitigate voltage and current disturbances [16].

The UPQC consists of two voltage source converters connected in series and shunt configuration. The shunt converter compensates current harmonics and reactive power, while the series converter mitigates voltage disturbances such as sag and swell [17]. This coordinated operation enables the UPQC to provide comprehensive power quality improvement in distribution systems [18].

Recent studies have shown that integrating UPQC with renewable energy systems can significantly enhance grid stability and reduce harmonic distortion [19]. In solar PV-based EV charging stations, UPQC can maintain voltage regulation, improve power factor, and minimize total harmonic distortion (THD) [20].

Therefore, this research aims to investigate the effectiveness of UPQC in improving power quality in solar-integrated EV charging stations. The study focuses on modeling the system architecture, implementing control strategies, and evaluating the performance of UPQC under various operating conditions.

II. LITERATURE REVIEW

The increasing penetration of renewable energy systems and electric vehicles has intensified research efforts on improving power quality in modern power networks [21]. Several studies have highlighted the challenges associated with integrating EV charging stations with renewable energy sources such as solar PV systems.

Early research emphasized the impact of nonlinear loads and power electronic converters on harmonic distortion in distribution systems [22]. EV chargers, which typically employ AC-DC converters, draw nonlinear current from the grid and introduce harmonic distortion in the supply voltage [23]. These harmonics can cause overheating of transformers, increased losses in transmission lines, and malfunction of sensitive electronic equipment [24].

Researchers have investigated various mitigation techniques to address harmonic distortion in EV charging infrastructure. Passive filters were initially used to suppress specific harmonic frequencies; however, their performance is limited under varying load conditions [25]. Active power filters have been proposed as a more effective solution for compensating harmonic currents and improving system performance [26].

In recent years, custom power devices such as Dynamic Voltage Restorers (DVR), Distribution Static Compensators (DSTATCOM), and Unified Power Quality Conditioners (UPQC) have gained significant attention for power quality improvement [27]. Among these devices, the UPQC offers a comprehensive solution by compensating both current and voltage disturbances simultaneously [28].

Several researchers have explored the integration of UPQC in renewable energy systems. Studies have shown that UPQC can effectively mitigate voltage fluctuations and harmonic distortion in grid-connected solar PV systems [29]. By injecting compensating voltage and current, the device ensures stable power supply even under fluctuating generation conditions [30].

In the context of EV charging stations, UPQC has been used to maintain voltage stability and reduce harmonic distortion caused by high-power chargers [31]. The device can also provide reactive power compensation, which improves the power factor and reduces transmission losses [32].

Recent research has focused on intelligent control strategies for UPQC to enhance system performance. Advanced control techniques such as fuzzy logic controllers, neural networks, and sliding mode control have been proposed to optimize the operation of UPQC in renewable energy systems [33]. These control algorithms enable faster response and improved compensation accuracy [34].

Simulation studies have demonstrated that integrating UPQC with solar PV-based EV charging stations can significantly reduce total harmonic distortion and stabilize voltage levels [35]. For example, hybrid control strategies combining fuzzy logic and sliding mode control have shown promising results in reducing THD and maintaining DC link voltage stability [36].

Despite these advancements, challenges remain in designing efficient control strategies and optimizing system configuration for large-scale EV charging infrastructure [37]. Further research is needed to evaluate the performance of UPQC under different load conditions and renewable energy variability.

This study contributes to existing literature by developing a simulation-based model of a solar-integrated EV charging station equipped with UPQC and analyzing its effectiveness in improving power quality.

III. MATERIALS AND METHODS

This section describes the configuration of the proposed solar-integrated electric vehicle (EV) charging system and the methodology adopted for improving power quality using a Unified Power Quality Conditioner (UPQC). The study involves system modeling, control strategy development, and simulation-based performance evaluation. The main objective is to analyze how the UPQC can mitigate power quality disturbances such as harmonic distortion, voltage sag, voltage swell, and reactive power imbalance in a solar-assisted EV charging infrastructure.

3.1 System Configuration

The proposed system consists of four main components: a solar photovoltaic (PV) generation unit, a grid-connected inverter, an EV charging station, and a Unified Power Quality Conditioner. These components are interconnected at the point of common coupling (PCC) in the distribution network. The grid acts as a backup power source when solar generation is insufficient to meet the charging demand of electric vehicles.

The solar PV system converts solar energy into direct current (DC) electricity using photovoltaic modules. Multiple PV modules are connected in series and parallel combinations to obtain the desired voltage and power rating. The DC output from the PV array is supplied to a DC-DC boost converter, which regulates the output voltage and maintains a stable DC link voltage. The regulated DC power is then converted into alternating current (AC) using a grid-connected inverter.

The inverter plays a crucial role in synchronizing the solar PV output with the grid. It ensures that the generated power matches the grid voltage, frequency, and phase. However, switching operations of the inverter may introduce harmonics into the distribution system. Therefore, proper control techniques are necessary to maintain acceptable power quality levels.

The EV charging station consists of multiple charging units that supply electrical energy to electric vehicles. Each charging unit typically includes an AC-DC rectifier followed by a DC-DC converter that regulates the charging current according to battery requirements. These converters behave as nonlinear loads and draw distorted current from the supply, which leads to harmonic generation and deterioration of power quality.

To address these issues, a Unified Power Quality Conditioner is installed at the point of common coupling between the grid and the EV charging station. The UPQC operates as a custom power device capable of compensating both voltage and current disturbances simultaneously. It consists of two voltage source converters connected in series and shunt configuration through a common DC link capacitor.

3.2 Unified Power Quality Conditioner Structure

The UPQC comprises two main active power filters: the series active filter and the shunt active filter. These filters operate together to eliminate power quality disturbances in the system.

The series converter is connected in series with the supply line through an injection transformer. Its primary function is to compensate voltage-related disturbances such as voltage sag, voltage swell, voltage imbalance, and harmonic distortion in the supply voltage. The converter injects a compensating voltage into the line so that the load receives a balanced and distortion-free voltage waveform.

The shunt converter is connected in parallel with the distribution system at the PCC. Its main purpose is to eliminate current harmonics generated by nonlinear loads such as EV chargers. The shunt converter injects compensating current into the system to ensure that the current drawn from the grid remains sinusoidal. Additionally, it provides reactive power compensation, which improves the overall power factor of the system.

Both converters share a common DC link capacitor that facilitates energy exchange between the series and shunt converters. The capacitor also helps maintain a constant DC voltage required for proper operation of the converters.

3.3 Control Strategy

An effective control strategy is essential for the proper operation of the UPQC. The control system continuously monitors voltage and current signals at the point of common coupling and generates appropriate reference signals for the converters.

The control algorithm consists of three major stages: signal measurement, reference signal generation, and pulse width modulation control. First, voltage and current signals are measured using sensors installed in the distribution system. These signals are processed to identify disturbances such as harmonic distortion, voltage sag, and reactive power imbalance.

In the second stage, reference signals for the compensating voltage and current are generated using instantaneous reactive power theory. This method separates the fundamental and harmonic components of the measured signals and determines the required compensation signals.

The third stage involves the generation of switching signals for the voltage source converters using a pulse width modulation (PWM) technique. The PWM controller compares the reference signals with carrier signals to produce gating pulses for the semiconductor switches. These switching pulses control the operation of the converters and enable accurate compensation of power quality disturbances.

3.4 Simulation Model

To evaluate the effectiveness of the proposed system, a simulation model is developed using power system simulation software. The simulation environment allows detailed analysis of the system under different operating conditions.

The model includes a solar PV array with a capacity of approximately 50 kW connected to a DC-DC boost converter. The boost converter regulates the PV output voltage and maintains a stable DC link voltage. A three-phase voltage source inverter converts the DC power into AC and connects the solar generation to the grid.

The EV charging station is modeled as a nonlinear load with a total power demand of approximately 40 kW. The charging units include rectifier and converter circuits that simulate the behavior of real EV chargers.

The UPQC is implemented using two voltage source converters connected in series and shunt configuration. A DC link capacitor is placed between the converters to facilitate energy exchange. Control algorithms are integrated into the model to regulate the operation of the converters and ensure effective compensation.

3.5 Performance Evaluation

The performance of the proposed system is evaluated by analyzing key power quality parameters. These parameters include total harmonic distortion of current and voltage, power factor, voltage regulation, and reactive power compensation.

Different operating scenarios are simulated, including variations in solar irradiation, changes in EV charging load, and disturbances such as voltage sag and swell. The system performance is compared with and without UPQC compensation to assess the effectiveness of the proposed approach.

The results obtained from the simulation provide insights into the capability of the UPQC to maintain stable voltage levels, reduce harmonic distortion, and improve overall power quality in solar-integrated EV charging stations. These findings form the basis for the discussion presented in the subsequent section.

IV. RESULTS AND DISCUSSION

The performance of the proposed solar-integrated electric vehicle (EV) charging system with the Unified Power Quality Conditioner (UPQC) was evaluated through detailed simulation analysis. The objective of this analysis was to examine the effectiveness of the UPQC in mitigating power quality disturbances caused by nonlinear EV charging loads and fluctuating solar photovoltaic (PV) generation. Key parameters such as Total Harmonic Distortion (THD), voltage stability, reactive power compensation, and power factor improvement were analyzed under different operating conditions.

4.1 Harmonic Distortion Analysis

One of the major challenges in EV charging infrastructure is the presence of harmonic currents generated by power electronic converters. In the proposed system, the EV charging units consist of AC-DC rectifiers and DC-DC converters, which behave as nonlinear loads and draw distorted currents from the supply. These harmonic currents propagate through the distribution network and may affect other connected loads.

The simulation results indicated that when the EV charging station operated without any compensation device, the current waveform was significantly distorted. The calculated Total Harmonic Distortion of the supply current was approximately 18%, which exceeds the recommended limits specified by power quality standards such as IEEE guidelines. High harmonic distortion may lead to increased heating in transformers, excessive losses in cables, and reduced lifespan of electrical equipment.

After integrating the UPQC into the system, the harmonic distortion was significantly reduced. The shunt active filter of the UPQC generated compensating currents that cancelled the harmonic components drawn by the EV chargers. As a result, the current drawn from the grid became nearly sinusoidal. The THD value decreased to around 4%, which falls within acceptable power quality limits. This improvement demonstrates the effectiveness of the UPQC in harmonic mitigation for EV charging applications.

4.2 Voltage Sag and Swell Compensation

Voltage disturbances such as sag and swell are common in distribution networks, particularly when large loads are connected or disconnected suddenly. In EV charging stations, simultaneous charging of multiple vehicles may cause a temporary drop in voltage, resulting in voltage sag conditions. Similarly, fluctuations in solar PV generation can lead to voltage swell or instability in the system.

To evaluate the performance of the proposed system under such disturbances, voltage sag and swell conditions were simulated. Without UPQC compensation, the load voltage experienced noticeable fluctuations during these disturbances. Voltage sag conditions reduced the load voltage to approximately 80% of its nominal value, which could negatively affect the performance of sensitive electronic equipment.

When the UPQC was activated, the series converter injected a compensating voltage into the supply line. This injected voltage effectively restored the load voltage to its nominal level even during sag or swell conditions. The load voltage waveform remained stable and balanced throughout the disturbance period. This result confirms that the UPQC can successfully maintain voltage stability in solar-integrated EV charging systems.

4.3 Reactive Power Compensation and Power Factor Improvement

Reactive power management is another important aspect of maintaining power quality in distribution networks. Nonlinear loads such as EV chargers typically consume reactive power, which reduces the overall power factor of the system. A low power factor leads to increased transmission losses and inefficient utilization of electrical infrastructure.

In the simulation study, the power factor of the system without UPQC compensation was observed to be approximately 0.85 lagging. This indicates the presence of significant reactive power demand in the system. When the UPQC was introduced, the shunt converter supplied the required reactive power to the load. This compensation reduced the reactive power drawn from the grid.

Consequently, the system power factor improved significantly and approached unity (approximately 0.99). The improved power factor not only reduces transmission losses but also enhances the overall efficiency of the power system.

4.4 System Stability under Solar Variability

Solar PV generation is inherently intermittent due to variations in solar irradiation caused by weather conditions. These fluctuations can affect the stability of EV charging infrastructure if proper control mechanisms are not implemented.

The simulation results demonstrated that the presence of the UPQC improved system stability during solar power fluctuations. The device maintained a stable voltage profile at the point of common coupling and ensured continuous power supply to the EV charging station. The DC link capacitor also helped regulate energy flow between the series and shunt converters, enabling efficient compensation during dynamic operating conditions.

Overall, the results confirm that the UPQC significantly enhances power quality in solar-integrated EV charging stations by reducing harmonic distortion, stabilizing voltage levels, improving power factor, and maintaining system reliability under varying operating conditions.

V. CONCLUSION

The rapid growth of electric vehicles and renewable energy technologies has significantly increased the complexity of modern power distribution systems. Solar photovoltaic (PV) integrated EV charging stations offer an environmentally sustainable solution for meeting future transportation energy demands. However, the combination of renewable energy generation and high-power EV charging loads introduces several power quality challenges in distribution networks. These challenges include harmonic distortion, voltage fluctuations, reactive power imbalance, and instability caused by the intermittent nature of solar energy. If not properly managed, these issues can reduce system efficiency, damage electrical equipment, and compromise the reliability of the power supply.

This study investigated the application of a Unified Power Quality Conditioner (UPQC) to improve power quality in solar-integrated electric vehicle charging stations. The proposed system consisted of a solar PV array connected to a distribution grid through a power electronic inverter, while multiple EV charging units acted as nonlinear loads. A UPQC was installed at the point of common coupling to mitigate power quality disturbances generated by both the renewable energy system and the charging infrastructure.

Simulation results demonstrated that the UPQC is highly effective in compensating for both voltage and current related disturbances in the system. The shunt active filter successfully reduced harmonic currents generated by EV chargers, resulting in a significant reduction in Total Harmonic Distortion (THD) of the supply current. The series active filter compensated for voltage disturbances such as voltage sag and swell, ensuring that the load received a stable and balanced voltage waveform. In addition, the UPQC provided reactive power compensation, which improved the system power factor and reduced the reactive power demand from the grid.

Another important outcome of the study was the improvement in system stability during fluctuations in solar PV generation. The UPQC maintained stable voltage levels at the point of common coupling and ensured continuous operation of the EV charging station even under varying solar irradiation conditions. This capability is particularly important for future smart grid systems where renewable energy penetration is expected to increase significantly.

Overall, the results confirm that integrating a UPQC into solar-powered EV charging infrastructure can greatly enhance power quality and system reliability. The proposed approach ensures efficient utilization of renewable energy resources while maintaining stable and high-quality power supply for EV charging operations. Therefore, UPQC technology represents a promising solution for addressing power quality challenges in modern renewable energy-based transportation systems.

Future research may focus on implementing advanced control algorithms, real-time hardware validation, and optimization of UPQC design for large-scale EV charging networks within smart grid environments.

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