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Review on Power Quality Enhancement Using Electric Vehicle Charging Stations with Unified Power Quality Conditioner

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ABSTRACT
The rapid integration of electric vehicle (EV) charging infrastructure into modern power distribution systems has introduced significant challenges related to power quality, including voltage sag/swell, harmonic distortion, reactive power imbalance, and load variability. This review paper presents a comprehensive analysis of power quality enhancement techniques using Electric Vehicle Charging Stations (EVCS) integrated with a Unified Power Quality Conditioner (UPQC). The UPQC, a versatile custom power device combining series and shunt active filters, is explored for its capability to simultaneously mitigate supply- and load-side disturbances in EV-dominated grids. The study examines various control strategies, including synchronous reference frame (SRF), instantaneous reactive power (p–q) theory, and artificial intelligence-based controllers, for efficient operation of UPQC in EV charging environments. Furthermore, the role of bidirectional EV chargers (Vehicle-to-Grid, V2G) is discussed in supporting grid stability and improving overall power quality. A comparative evaluation of existing methodologies highlights improvements in total harmonic distortion (THD), voltage regulation, and system reliability. The review also identifies key research gaps, such as real-time adaptive control, integration with renewable energy sources, and scalability challenges in smart grid frameworks. The findings demonstrate that the coordinated use of EVCS and UPQC offers a promising solution for enhancing power quality in future intelligent power systems.

Keywords- Power Quality, Electric Vehicle Charging Stations (EVCS), Unified Power Quality Conditioner (UPQC), Total Harmonic Distortion (THD), Voltage Sag and Swell, Reactive Power Compensation, Vehicle-to-Grid (V2G), Custom Power Devices, Smart Grid, Artificial Intelligence Control Techniques

I. INTRODUCTION
Power quality is a predominant factor in the efficiency and security of grids and, more freshly, of smart grids, and is likely to be strongly affected by PEV development over the forthcoming years. EV interface systems use power electronic converters because of their operating principles and the nature of its switching power semiconductor components, and these are highly nonlinear systems. Therefore, in the input current of the converter, high levels of harmonics are typically present and

these are generally handled with using PWM control and filtering. Producers say that their converters, both in charging and regeneration modes, generate good power quality (With regard mainly about harmonics & the power factor) India may need a minimum of 1.32 million charging stations by 2030 to facilitate the rapid adoption of electric vehicles (EVs), according to a report released by the Confederation of Indian Industry (CII) on 'Charging Infrastructure for Electric Vehicle'. Electric vehicle charging uses a large number of switch mode Power supplies where it converts AC to DC Power to charge the battery. This conversion process ,in turn , generate harmonics predominantly 3rd ,5th and 7th .The third harmonic don't get cancelled at star point and get added up in the neutral, increasing the neutral current drastically . This overheats the neutral and increases the neutral to earth voltage, which might be a major cause of concern for other electronic equipment in vicinity. In addition to this, most of the load distribution is balanced, but due to random charging patterns, we will always have instantaneous unbalance in the 3 phases All these are major concern related to power quality caused by EV chargers.

II. POWER QUALITY

Power Quality (PQ) has two aspects - Voltage and Current which are directly linked to each other. We can define power quality for current based on four load parameters i.e. Power factor, Harmonics, Unbalance and Neutral. These four parameters can directly assess the impact on the grid due to load characteristics. In the case of voltage, the major issues are Unbalance, Sags, Swells, Interruptions etc - these are factors that define the power quality of the source side. Power Quality is important in order to safeguard the proper functioning of the power grid system and the loads connected to it. PQ requirements should be a characteristic of both parts of the system, i.e. the energy supplied by the power grid, as well as the energy consumed by the equipment connected to the grid.

Impact Of Ev Charging On Power Quality

In India, there are certain regulations in place for Power Quality, and they are applicable to all LT and HT consumers. Globally, in 2011 SAE issued power quality requirements for plug-in electri vehicle (PEV) chargers in response to rising sales of PEVs and concerns about their potential impact on utility systems and on other devices connected to them. Electrical power is delivered upon demand, and utility systems are impacted by the demand of power and the duration of that demand. Distinctions must be made about real power, which does work, and apparent power, which is the impact on the electrical system. With respect to harmonics, IEEE 519-2014 standard forms the basic guideline for harmonic regulation in India. The billing as recommended by CEA has to be through KVAh and most state have already implemented the same. KVAh billing automatically takes care of any deviation in power factor and penalises the user for leading as well as lagging power factor. Since the powe quality recommended practice was issued, interest has emerged for measuring and regulating power quality and energy efficiency of EV charging systems

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and work is happening on improvin the specifications of the EV chargers so that they are designed to take care of PQ issues internally.

III. LITERATURE REVIEW

Baseem Khan et al. [1] The growing integration of renewable energy sources into microgrids has heightened the need for effective power quality (PQ) management solutions. This scoping review investigates the deployment of Unified Power Quality Conditioner (UPQC) and its variants as mitigation technologies for power quality disturbances in microgrid environments. A systematic search across major databases was conducted, which yielded 1700 records. From these records, 51 studies met the inclusion criteria based on the population concept context framework. Analysis revealed a predominant focus on grid-connected microgrids, with harmonics, voltage sags, and power factor correction as the most addressed PQ issues. Classical control strategies such as PI and synchronous reference frame control were most common, though intelligent methods like fuzzy logic, ANN, and hybrid approaches demonstrated higher PQ improvement performance. While most studies relied on MATLAB/Simulink simulations, a notable portion also incorporated real-time hardware-based validation using platforms like OPAL-RT and dSPACE. Geographically, research was dominated by contributions from India and China. The review identifies key research gaps in experimental validation, long-term stability assessment, and hybrid microgrid configurations. This synthesis offers a consolidated view of the technical landscape and highlights future research directions in UPQC-based PQ solutions for resilient and efficient microgrids.

Mohamed M. Refaat et al. [2] With the increasing deployment of microgrids and the growing integration of electric vehicles, maintaining power quality has become a significant challenge. Distribution Static Compensators (DSTATCOMs) are widely used for fast-acting reactive power compensation and voltage support, making them well-suited to the dynamic operating conditions of microgrids and renewable-integrated systems. However, conventional controllers, such as proportional-integral (PI) and fractional-order PI (FOPI) controllers, often exhibit limited dynamic response. Similarly, traditional Fuzzy Logic Controllers (FLCs) are constrained by the size and complexity of their rule base. To overcome these limitations, this study introduces an optimized Simplified Fractional-Order Fuzzy Logic Controller (SFO-FLC), designed to reduce computational complexity by minimizing the number of fuzzy inference rules without compromising control performance. A weighted-sum approach, implemented using the Tornado optimization algorithm with Coriolis force modeling, enables the transformation of a conventional two-input FLC into an efficient single-input structure. Moreover, the proposed controller enhances robustness by incorporating the fractional-order derivative of the input signal and the fractional-order integral of the output signal into the fuzzy inference system.

Krishna Sarker et al. [3] The proposed integrated system combines of fuel cell (FC), photovoltaic (PV), battery, Z-source and Biogeography-Based Optimization (BBO) based Unified Power Quality Conditioner (UPQC) compensator aims to provide a high-quality power supply to sensitive loads, such as electrical, electronics, medical equipment, Electrical Vehicles (EV), or critical industrial processes. It can regulate voltage, mitigate power disturbances (e.g., voltage sags, swells, flicker, voltage interruption, harmonics, reactive power etc.), and ensure a stable power supply. Additionally, it can facilitate EV charging stations by managing the power flow and optimizing charging processes. The PV or FC based Z-source inverter can control and regulate power flow in both directions. It operates with a unique impedance network, allowing for voltage boosting or bucking. The Z-source inverter enhances the flexibility and control of power flow in the system. The fuel cell generates electricity through an electrochemical process, typically using hydrogen as a fuel source, while the PV array converts sunlight into electrical energy. The FC-PV system provides a renewable and clean energy source. The battery serves as an energy storage device within the integrated UPQC system. It stores excess energy produced by the FC-PV system or from the grid during off-peak hours and releases it when needed, contributing to load balancing and stability.

Yunchao Shi et al. [4] This study proposes a novel resilience-oriented optimization framework for post-outage microgrid (MG) formation, integrating electric vehicle (EV) parking lots into radial and meshed distribution networks. The main contribution lies in a unified modeling scheme that enforces graph-theoretic radiality and connectivity constraints, while simultaneously managing complex power flows, voltage regulation, and EV charging dynamics. Radial and looped MGs are formulated using enhanced DistFlow models, with precise voltage and power loss calculations under both hierarchical and redundant topologies. A new path-based recovery model is introduced for meshed networks, utilizing pre-computed k-shortest paths to ensure loop integrity. The EVs' real-time charging/discharging, battery constraints, and inverter limits are identified through an integrated EV parking lot model.

Zia Ullah et al. [5] The accelerating integration of electric vehicles (EVs) and renewable energy sources (RESs) into modern power systems marks a critical step toward low-carbon, efficient, and resilient energy infrastructure. Central to this transition is the development of electric vehicle charging stations (EVCSs), which present various design, control, and operational challenges. This review offers a comprehensive evaluation of EV and RES integration, with a particular focus on EVCS infrastructure, power converter topologies, and system-level coordination. A bibliometric analysis of 1,725 Scopus-indexed documents from the past two decades was conducted using VOSviewer to uncover research trends, thematic clusters, and collaboration patterns. In parallel, technical aspects such as grid impacts, energy management models, charging strategies, and communication protocols are critically examined.

Youness Hakam et al. [6] This study focuses on the control of an OFF-board electric vehicle (EV) charging station, providing a cost-efficient solution for managing high grid demand periods. By integrating a Kalman filter with Artificial Neural Networks (ANN) for Maximum Power Point Tracking (MPPT), the system optimizes energy capture from photovoltaic (PV) panels, even in severe weather conditions and partial shading. Unlike traditional MPPT methods, which face challenges with multiple peaks in the Power–Voltage (P–V) curve, the hybrid algorithm enhances tracking accuracy, reduces errors, and cuts tracking time by up to 99.93%.

Pavel Stanko et al. [7] The European Union (EU) aims to reduce greenhouse gas emissions by 2030 and therefore a proposal has been accepted to improve publicly accessible charging and refueling infrastructure for alternative fuels. This will result in an increasing number of electric vehicles charging stations, which can negatively impact the power grid. Therefore, this paper investigates the impact of electric vehicle charging by a particular charging station on the grid from a power quality perspective.

Tapankumar Trivedi et al. [8] The Unified Power Quality Conditioner (UPQC) is a promising solution for mitigating multiple Power Quality(PQ) issues in distribution systems, including harmonics, poor power factor, voltage sag/swell and voltage imbalance. The conventional Sliding Mode Controller (SMC) in UPQCs suffers from wide switching frequency variations, chattering problems, and inherent active and reactive power coupling. This study proposes a nonlinear control method, Sliding Mode-based Direct Power Control (SMC-DPC), for the simultaneous regulation of the shunt and series compensators in a UPQC. By optimizing voltage vector selection based on real-time power errors, the proposed method effectively mitigates chattering, and reduces switching frequency variations, and ensures precise tracking of instantaneous active and reactive powers even in the presence of coupling effects.

Abhinav Srivastava et al. [9] The adoption of electric vehicles is part of a broader effort to address environmental challenges, reduce greenhouse gas emissions, and transition to more sustainable energy systems. However, their integration into the electrical grid through grid-to-vehicle (G2V) and vehicle-to-grid (V2G) charging and discharging mechanisms may cause problems for the existing power grid such as voltage unbalances, transformer failure, and harmonic distortion may arise. These issues can negatively impact grid stability and power quality due to the unsteady nature of power sources and the unpredictability of electric vehicle loads This research examines and evaluates the problems associated with integrating electric vehicles into electrical networks. the research and strategies discussed in this article demonstrate that these challenges can be effectively mitigated.

Bin Yao et al. [10] The rapid adoption of hydrogen vehicles highlights the necessity for strategically planned hydrogen refueling infrastructures to ensure efficient, low-carbon, and user-friendly transportation. This paper develops a hybrid cloud theory–based stochastic optimization framework for the optimal siting of hydrogen vehicle charging stations (HVCS) in renewable-

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integrated distribution systems, explicitly considering carbon restriction policies and user range anxiety. To capture the uncertainties associated with renewable generation, hydrogen demand, and load variations, cloud theory is applied to generate stochastic cloud droplets that represent both randomness and fuzziness, thereby constructing a robust uncertainty-aware planning model. The optimization problem is formulated as a multi-objective model, aiming to minimize active power losses, emission costs, and investment/operational expenditures, while maximizing renewable utilization and hydrogen supply reliability.

IV. EXPECTED OUTCOMES

The only long-term solution to produce efficient energy is to improve the power quality at grid-connected solar EV charging stations. The proposed system expertly combines smart charging infrastructure for electric and hybrid vehicles with solar photovoltaic (PV) power. By combining a one stage converter design with a novel control method, we can achieve bidirectional power flow, reactive power accounting, and power generation that meets UPFC criteria. The technology can adjust to real-life situations, controls charging and discharging, reduces harmonics, and keeps the grid synchronized. Using a time management strategy allows for a safe transition between grid and island modes. This means that even if the power goes out, the system can continue to function.

V. CONCLUSION

The increasing penetration of Electric Vehicle Charging Stations (EVCS) in modern distribution networks has intensified power quality challenges due to their nonlinear and dynamic charging characteristics. This review establishes that the integration of a Unified Power Quality Conditioner (UPQC) with EVCS provides an effective and comprehensive solution for mitigating key disturbances such as voltage sag/swell, harmonic distortion, reactive power imbalance, and load fluctuations. The dual functionality of UPQC, combining both series and shunt compensation, enables simultaneous enhancement of source- and load-side power quality, making it highly suitable for EV-integrated smart grids.

The analysis of various control strategies, including conventional methods such as synchronous reference frame (SRF) and instantaneous reactive power (p–q) theory, along with emerging artificial intelligence-based controllers, indicates significant improvements in system performance, particularly in reducing Total Harmonic Distortion (THD) and improving voltage stability. Additionally, the incorporation of bidirectional charging and Vehicle-to-Grid (V2G) capabilities further strengthens grid support by enabling active participation of EVs in power quality management.

However, despite these advancements, several challenges remain, including real-time adaptive control under highly variable EV loads, coordination with renewable energy sources, cost-effective implementation, and scalability in large distribution networks. Future research should focus on intelligent, data-driven control techniques, robust optimization methods, and integrated energy management frameworks to fully exploit the potential of UPQC-assisted EVCS.

Overall, the coordinated deployment of EV charging infrastructure with UPQC represents a promising pathway toward achieving enhanced power quality, improved grid reliability, and sustainable operation of next-generation power systems.

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