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ENHANCING POWER QUALITY IN THREE-PHASE GRID-CONNECTED PV-BASED EV CHARGING STATIONS: A COMPREHENSIVE REVIEW

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Abstract- In the area of sustainable power structure, hybrid photovoltaics (PV) Electric vehicle (EV) charging station technology is very promising. However, this combination comes with challenges related to power penalties, as the discontinuous nature of photovoltaic technology and the dynamic charging characteristics of electric vehicles can cause voltages fluctuations, harmonization and imbalance situations in the grid. This review contains techniques to improve power satisfaction in three-phase grid connected PV based EV charging station. It scans the landscape for energy satisfaction issues in grid-related systems, explain the details of PV based EV integration and outlines the operational scope and techniques to mitigate voltage instability, harmonic distortion and reactive energy unbalance. Additionally, the review validates good operating patterns, models, predictive management and virtual synchronous generators prominently show the ability to improve the power, by examining case studies, experimental effects, and new developments. This review summarizes the evolving strategies and trends to highlight sustainable existence of PV based EV charging stations within the grid, ensuring the best grid efficiency.

Keywords- PV, EV, charging, power quality, grid-connected, enhancement, strategies.

I. INTRODUCTION

The integration of renewable electricity assets and electric vehicles (EVs) into the existing energy grid is changing the energy landscape, providing answers to all environmental concerns and sustainable transportation needs. Among these innovations, photovoltaic (PV) structures have become a viable method for smooth energy production. At the same time, the widespread use of electric vehicles reduces greenhouse gas emissions and dependence on fossil fuels. This synergy has led to the emergence of PV based EV charging stations as a focus of research and innovation, contributing to the completion of smart grids and eco-friendly urban mobility (Abubakr et al. associates, 2022).

However, as the deployment of PV based EV charging stations accelerates, the interaction between these systems and the grid will poses multiple challenges that require attention (Alrubaie et al., 2023). A major concern is the resilience of the grid. Power quality encompasses a range of attributes that represent the consistency and reliability of the power supplied. Voltage balance, harmonic distortion, frequency variation, and reactive power unbalance are some of the aspects of quality power that can be affected by the combination of the PV and EV charger. The discontinuous nature of PV technology, encouraged by climatic conditions, coupled with the dynamic and possibly excessive power demand from electric vehicle charging, can lead to voltage fluctuations and harmonics that disrupt grid operation and degrade the efficient power supply connected to consumers (Anis Ur Rehman et al., 2023).

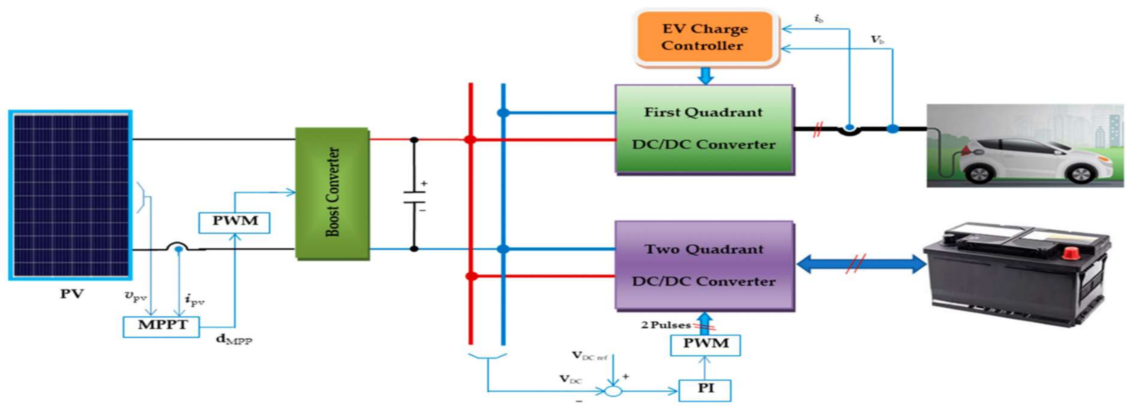

Fig 1: Design of an Electric vehicle charging station which was supplied by Photovoltaic Energy (Anis Ur Rehman et al., 2023)

This review paper aims to comprehensively address issues related to large-scale power upgrades in three-phase grid-related PV-based EV charging stations. The importance of this issue is underscored by the interdependence of sustained power integration and grid balance and reliability. The integration of PV structures creates fluctuations in the grid, without an effective management strategies, this change can have a significant impact on power supply. Therefore, to seamlessly integrate this technology into existing power infrastructure, it is important to improve strategies to mitigate energy issues while enjoying the benefits of PV based EV charging systems (Choudhury et al. 2019). During this review process, we are able to conduct a detailed survey of the existing literature, covering all theoretical frameworks and its practical implementations. Various strength, high-quality demanding situations precise to PV based EV charging stations might be analyzed and observed via an in-depth investigation of manipulate techniques and strategies employed to mitigate those demanding situations. Advanced management patterns, model predictive control, and virtual synchronous turbines may be assessed for their ability to improve power quality (Dhikale & Shriwatava, 2022). By shedding light on the complexities of electricity satisfaction enhancement in PV based EV charging stations, this review aim to offer complete information on the current state of research and improvement in this field. Insights from case studies, experimental reviews, and emerging technologies might be synthesized to highlight the simplest techniques for reaching optimal strength satisfactory while understanding the environmental and electricity desires related to PV based EV charging structures. Ultimately, the paper wishes to make a contribution to the understanding base needed to persuade the evolution of grid-related PV based EV charging stations towards a direction characterized by sustainability, reliability, and efficiency in power distribution efficiency (Heenkenda et al., 2023).

II. POWER QUALITY IN GRID-CONNECTED SYSTEMS

Superlative energy in grid-connected structures has been the subject of much research because of its immediate impact on the stability, reliability and efficiency of the modern power grid.

Previous research has explored various aspects of power quality resistance problems, such as voltage fluctuations, harmonic distortion, voltage sags, and reactive force unbalance. Notably, surveys by researchers including Abubakr et al. (2022), emphasizes the negative consequences of voltage drops on sensitive industrial systems, emphasizing the need for effective mitigation techniques. In addition, the works of R. C. Heenkenda et al. (2023) provided comprehensive information on the characterization and analysis of particular electrical disturbances, thereby contributing to the development of measurement and evaluation techniques. In addition, the study by Alrubaie et al. (2023) on active power filters paved the way for advanced payback methods for reducing harmonic currents, thereby reducing harmonic distortion in grid connected systems.

In the context of renewable energy integration, research has focused on the influence of discontinuous sources such as photovoltaic systems on electricity production. The work of Bertling Tjernberg et al. (2008) explored voltage fluctuations on photovoltaic structures and proposed management techniques to mitigate these fluctuations. In addition, as electric vehicles became prominent, researchers including Anis Ur Rehman et al. (2023), tested the potential impact of electric vehicle charging on high-quality energy, highlighting the need for coordination and management mechanisms to avoid grid overload and voltage bias. Several researchers have studied control techniques to advance power generation in grid-connected systems. For example, Anis Ur Rehman et al. (2023) proposed a voltage control method purely based on reactive power injection to regulate the voltage level at the time of network failure. In the context of harmonic attenuation, the work of Choudhury et al. (2019) on active power filters using advanced management strategies have established strong harmonic suppression capabilities. While previous studies have contributed significantly to expertise in power quality issues and mitigation strategies, the dynamic interaction between PV based EV charging stations and the grid poses new challenges which requires suitable solutions.

This comprehensive review aims to consolidate and expand on previous findings by focusing on power improvement strategies in the context of three-phase grid connected PV based EV charging stations. By synthesizing and analyzing the prevailing literature, this review offers an updated and comprehensive perspective on the state of modern research. It highlights the development of unique power handling techniques as well as demanding and pleasant situations resulting from the combination of photovoltaic and electrical technologies (Choudhury et al., 2019).

III. CONTROL STRATEGIES FOR POWER QUALITY IMPROVEMENT

Previous research has focused on control strategies to improve performance and significantly improve grid-tied systems, including advanced technologies that mitigate the adverse effects of voltage instability, harmonics, and other power problems. Remarkable research has explored different management strategies, demonstrating their effectiveness in maintaining network stability and improving network resilience at best. The synchronous voltage control strategy has been studied extensively.

The work done by Anis Ur Rehman et al. (2023)) introduced the concept of voltage regulation at the common coupling point (VRPCC), demonstrating how to minimize voltage fluctuations by controlling the injection of reactive power from distributed power generation devices (DG).Similarly, a study by Dhikale & Shrimatava (2022) demonstrated the effectiveness of adaptive neurofuzzy inference system (ANFIS)-based regulators for voltage regulation in grid-connected structures, especially in the presence of intermittent renewable energy sources. In the field of harmonics reduction, the use of electrically active filters (APFs) is always preferred.

The work of Anis Ur Rehman et al. (2023) pioneered the concept of Unified Power Quality Conditioning (UPQC), an APF-based tool capable of compensating for current voltage and power satisfaction issues simultaneously. On this basis, Heenkenda et al. (2023) extensively evaluated APF control strategies, analyzing their effectiveness in suppressing harmonic currents and improving power factors. With the incorporation of renewable assests such as photovoltaics, advanced control methods have been employed to ensure satisfactory performance. Research by Rehman et al. (2023) proposed a set of maximum power point tracking (MPPT) rules for photovoltaic structures to improve efficiency and reduce voltage fluctuations under different solar irradiance conditions.

In addition, Jain et al. (2023) added a control method using photovoltaic inverters to actively control the voltage profile and minimize voltage surge problems in low voltage grid. The development of control strategies is notable as a combination of artificial intelligence (AI) and device dominance strategies. In particular, the work of Jaraniya & Kumar (2022) tested the applicability of AI-based control strategies, specifically using depth extension to acquire knowledge of the voltage law of grid-related systems.

Although previous research has contributed significantly to the knowledge of management techniques for performance enhancement, the growing model of PV based EV charging stations poses special challenges that require to explore new and adaptive strategies. This comprehensive review aims to synthesize these current manipulation techniques and expand the discourse by primarily addressing their relevance and effectiveness in the context of grid connected PV based EV charging stations. Expand the discussion by clarifying how it will be coordinated and how it can be used to improve power quality while addressing the complexity of PV and EV integration (Javed et al., 2019).

IV. IMPACT OF PV VARIABILITY ON POWER QUALITY

The impact of photovoltaic (PV) variability on energy comfort has been a focus of research due to the intermittent and unpredictable nature of solar energy production. Previous studies have extensively investigated the effects of PV fluctuations on grid balancing, voltage regulation, and various energy optimum indices. Jane et al. (2023) investigated voltage fluctuations induced by rapid changes in solar irradiance, also called cloud effects.

This study highlighted the need for correct forecasting methods to predict changes in PV power and mitigate the impact on grid voltage balance. Furthermore, Javed et al. (2019) emphasized that PV fluctuations can contribute to voltage instability and flicker, especially in rapidly changing weather conditions. Voltage instability due to PV fluctuations has also been studied by Jaraniya & Kumar (2022). Their assessment showed that fluctuations in photovoltaic power can lead to voltage deviations and sags, especially in vulnerable distribution networks. These voltage disturbances can affect sensitive equipment and require effective control strategies to maintain sufficient voltage.

In addition, the interaction between PV structure and resistive elements was investigated. A study by Jha & Shaik (2023) investigated the effect of PV variation on power aspect variation.

The study found that the intermittent nature of photovoltaic generation can cause reactive power fluctuations, affecting power levels and potentially requiring reactive power compensation measures. In terms of effective corrective action, the study of Jumani et al. (2020) proposed combining electric garage systems to deal with fluctuations in photovoltaic production. The study confirmed that utilities can best improve power by successfully mitigating voltage fluctuations caused by PV fluctuations and providing immediate payback. Previous research has contributed significantly to expert knowledge on the effect of PV fluctuations on energy satisfaction. The combination of PV based EV charging stations creates new dynamics that need to be taken into account. Based on these findings, the aim of this overall study is to investigate the precise impact of PV fluctuations on power delivery in the context of three phase grid-connected PV-based EV charging stations. By reading the existing literature and synthesizing the results, this review aims to provide an overview of the demanding situations posed by photovoltaic variability to maintain excellent power and focus on techniques that ensure reliable and robust operation of such embedded structures (Khan et al., 2017).

V. PV-BASED EV CHARGING STATIONS

The emergence of photovoltaic (PV) based electric vehicle (EV) charging stations has attracted considerable attention in the field of sustainable energy and transportation structures. Previous studies have extensively explored many aspects of PV based EV charging stations, from technological components to financial and environmental impacts. Research by Khan et al. (2017) studied the design and optimization of PV based EV charging infrastructure. The evaluation process focuses on determining the size of PV structures and battery size for green EV charging, taking into account factors such as solar irradiation version and charging configuration. These studies have laid the foundation for the integration of renewable energy sources in electric vehicle charging, thereby improving their sustainability. In terms of grid integration, the work of M. Monica Subashini and V. Sumathi (2023) tested demanding situations and opportunities for PV based EV charging in the grid operations.

The study highlights the potential benefits of bi-directional current between electric vehicles and the grid, enabling car-to-grid (V2G) capabilities that balance the grid and help during periods of high demand. In addition, the financial viability of charging stations for PV based EV charging has also been considered. Studies, with the help of (Ma, 2019), evaluated the economic feasibility of these stations, taking into account factors such as investment costs, electricity costs and potential revenue streams related to electric vehicle charging. The observation highlights the importance of accurate cost-benefit analysis for the deployment of PV based EV charging infrastructure. Environmental impact is also the focus of the studies.

The study by Mane & Linus (2023) tested the life cycle assessment of PV based EV charging systems, taking into account their ability to reduce greenhouse gas emissions. Studies have confirmed that PV based EV charging stations can contribute to huge emissions reductions compared to traditional fossil fuel-based charging. Considering the dynamic interactions between PV structures, EV and grids, studies were carried out with the help of M. A. Khan et al. (2019), between PV technology and EV charging to maximize the use of renewable energy while ensuring grid balance. Observers suggested smart charging methods that adapt to PV output generation version and grid situations.This comprehensive review aims to build on these studies by providing an in-depth analysis of PV based EV charging stations in a three phase grid connection. By synthesizing current literature, this review sheds light on the technical, economic, environmental and operational factors of PV based EV charging stations while addressing the challenges and opportunities involved. The evolving landscape of sustainable mobility and force integration highlights the importance of holistic PV based EV charging stations, as they lie at the crossroads of renewable energy, transportation, and grid dynamics (Mohapatra et al., 2021).

VI. CASE STUDIES AND EXPERIMENTAL INVESTIGATIONS

1. REAL-WORLD IMPLEMENTATIONS OF PV-EV CHARGING STATIONS

Case studies and experimental investigations showing actual and international implementations of PV-EV charging stations provide valuable insight into the practical feasibility and overall performance of integrated structures. A number of notable examples have been presented in the literature to date, providing comprehensive information on the challenges and opportunities associated with the deployment of PV-EV charging stations.

The works by Nahar Al-Shamali et al. (2023) provided a case study of his PV integrated EV charging station in an urban environment. The study validated, a combination of solar shading and multiple charging factors for EVs, and showed how PV power is used for direct charging of EVs during the day. This case study provided an empirical record of the interaction of generation, consumption and grid, providing a rational blueprint for PV-EV integration in urban areas. Nasr Esfahani et al. (2022) studied a solar-powered public charging station for electric vehicles. By analyzing charging style, power flow, and user behavior, this study assesses the station's feasibility and ability to deliver economic and environmental benefits.

These studies emphasized the importance of matching station capacity to consumer demand and optimizing the size of PV machines to ensure a stable power supply. Regarding experimental studies, a study by Parashar et al. (2023), conducted a field test of a PV-EV charging station with storage function. The study demonstrated the benefits of combining solar energy technology with storage batteries to manipulate PV fluctuations and provide reliable EV charging services.

Experimental results demonstrated the self-sufficiency and controllability of grid interactions. Based on these case studies, Parashar et al. (2023) explored grid connected PV-EV charging stations within educational institutions. This study explores the overall technical performance of the station, but also considers grid impacts and other aspects of performance. The study highlighted the need for better operating strategies to harmonize the interaction of PV and EV while maintaining grid balance. Together these case studies and experimental investigations contribute to a comprehensive knowledge of the implementation of PV-EV charging stations. Analyzing real-world chances and experimental effects provides valuable insight into the technical, financial and environmental aspects of integrated systems. This evaluation aims to integrate and extend the knowledge gained from these studies, providing a summarized perspective on a number of reviews and results on the deployment of PV-EV charging stations in the context of three phase grid connections. (Rajesh Kumar Lenka et al., 2022).

2. PERFORMANCE EVALUATION OF POWER QUALITY ENHANCEMENT STRATEGIES

Case studies and experimental investigations of the overall performance of power quality improvement strategies provide essential insights into the effectiveness of different techniques in real-world scenarios. The available literature presents a number of studies evaluating the impact of these techniques on energy development.

Important contributions in this area came from Ram et al. (2022), who presented a test case for the application of an active force filter (APF) to minimize harmonics in a distribution network. The study evaluated harmonic distortion reduction and reactive power return through APF implementation, demonstrating its effectiveness in improving resistor quality by reducing voltage harmonics. Furthermore, the study, in collaboration with Shafiei and Ghasemi-Marzbali (2022), an experimental investigation was conducted to evaluate the performance of grid-connected photovoltaic systems equipped with dynamic voltage recovery device (DVR). By simulating voltage drop and swells, research has demonstrated that the function of the DVR is to quickly restore voltage and maintain good resistance standards during times of network disturbances. In the context of energy aspect regulation, the studies of Sharma et al. (2020) reviewed strategies for regulating the efficiency of capacitor banks and power components in the commercial sector. The study quantified the evolution of resistive elements and its impact on reducing reactive power consumption, revealing the possibility of achieving more consistent power quality and reducing grid losses. An extensive study by Shravan Kumar Yadav & Yadav (2021) evaluated the performance of superior processing techniques in microgrids with renewable energy plants. The study aimed to evaluate the effectiveness of management strategies in voltage regulation, harmonic mitigation and islanding detection. The results have provided valuable insights into the effectiveness of manipulative strategies to maintain stable energy in distributed power systems. Based on this study, the goal of this comprehensive review is to consolidate and enhance the overall performance evaluation information for power enhancing techniques.

By synthesizing lessons from case studies and empirical studies, this review aims to provide a composite perspective on the practical implications and effectiveness of these strategies in the context of three phase grid connectivity. The variety of studies and results presented in the existing literature contribute to a comprehensive assessment of major energy recovery strategies and their implications for modern power systems.

3. *COMPARATIVE ANALYSIS OF DIFFERENT APPROACHES*

A comparative evaluation of the different processes involved in the integration of photovoltaic (PV) structures and electric vehicle (EV) infrastructure was the focus of the research, providing insight into the effectiveness and interactions of different technologies. In particular, the study by Singh et al. (2021) compared centralized and distributed control techniques for PV-EV integration. The study emphasized that centralized control provides enhanced network control capabilities, while distributed control improves scalability and adaptability. Furthermore, Singh et al. (2018) provided a comparative assessment of battery sizing in the utilization of PV-EV integration, considering both PV-EV direct charging options and PV-battery -EV charging options. In this study, PV-EV direct charging was tested to provide immediate solar power availability, while PV-battery-EV charging offers increased flexibility and grid support capacity. In addition, a study using Uğur Mert Işik et al. (2023) compared unique energy-sharing techniques for his PV-EV charging stations such as load prioritization and bidirectional power float operation. The study found that bi-directional power wave management improves power distribution between electric vehicles and reduces congestion on the power grid during peak hours. Overall, these comparative analyzes highlight the importance of customized integration approaches based on specific objectives and system requirements, optimizing the benefits of PV-EV integration while addressing technical and operational challenges, provide valuable guidance on how to do so (Verma & Singh, 2020).

VII. CONCLUSION

In summary, the integration of photovoltaic (PV) systems into electric vehicle (EV) infrastructure has great potential to promote a sustainable energy ecosystem. A comprehensive literature review on power quality improvements, the impact of PV variability, control strategies, and real-world implementations concludes that PV based EV charging stations contribute to cleaner mobility and improved grid stability by providing a promising avenue. Previous studies have demonstrated innovative approaches to mitigate power quality issues, exploit PV variability, optimize control strategies, and demonstrate the feasibility of PV-EV integration in real-world environment. However, the dynamic interaction between renewable energy production, electric vehicle charging and grid operation is complex and requires continuous research and innovation. As the energy landscape evolves, maximizing the potential of PV based EV charging stations within a three-phase grid connection will require overcoming technical challenges, optimizing economics, and delivering environmental benefits. Strategic collaboration between academia, industry and policy makers to advance the path to a more sustainable and integrated energy future, ultimately transitioning to cleaner transport and more resilient power grids.

CHALLENGES AND FUTURE DIRECTIONS

Challenges and future directions in integrating photovoltaic (PV) systems into electric vehicle (EV) infrastructure include optimizing grid balance as PV fluctuates, improving seamless bi-directional power flow, intelligent advances in smart charging algorithms, effective integration of power grid, and promotion of regulatory frameworks allows for wider adoption. Addressing these challenges and directing research to definitive answers will accelerate the development of PV-EV architectures and ensure their role in building sustainable, resilient and robust ecosystems.

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