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Power Quality Enhancement in Microgrid for Grid Connected Electric Vehicle Charging Infrastructure – A Critical Review

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Abstract: In recent years, with the rapid adoption of EV charging stations and their integration into microgrids, maintaining a reliable and high-quality power supply has become crucial. This review examines the significance of power quality in microgrid environments with a focus on enhancing the charging infrastructure for electric vehicles (EVs) tied to the grid. The integration of electric vehicles (EVs) into microgrid-connected charging stations has brought forth challenges related to power quality, necessitating advanced techniques for enhancement. The study explores various methods, technologies, and strategies employed to address power quality issues in microgrids, specifically concerning EV charging infrastructure. Focusing on mitigating voltage fluctuations, harmonic distortions, and ensuring grid stability, this review examines various approaches. Advanced control algorithms, energy storage systems (ESS), active/passive filters, and smart grid technologies emerge as key solutions. Additionally, the abstract highlights the integration challenges of EV charging stations into microgrids and the evolving concept of vehicle-to-grid (V2G) technology. Furthermore, the review discusses challenges, future directions, and potential research avenues aimed at optimizing power quality within microgrids supporting EV charging infrastructure for a sustainable energy ecosystem.

Keywords: *Power Quality, Microgrid, Electric Vehicle Charging*

I. INTRODUCTION

Conventional automobiles are being substituted with plug-in hybrid electric vehicles (EVs) due to the release of hazardous gasses and environmental pollutants. Consequently, the usage of electric vehicles is rising. Renewable energy sources like solar power and electric vehicle chargers are essential for lowering our dependency on fossil fuels and are the natural evolution of our energy system [1]. In recent years, the growing integration of electric vehicles (EVs) into the power grid has presented new challenges and opportunities for the effective management of power quality within microgrid environments. The integration of electric vehicles (EVs) into microgrid-connected charging stations has revolutionized the transportation sector, introducing new complexities to the power grid. This paradigm shift, while promising in reducing carbon emissions and promoting sustainability, has concurrently posed challenges to the grid's power quality [2].

The surge in EV adoption has led to increased power demand, causing voltage fluctuations, harmonic distortions, and unbalanced loads within microgrids. These issues can adversely affect the grid's stability and reliability, compromising the performance of both charging stations and other connected electrical loads. Also demands robust and reliable charging infrastructure, emphasizing the need for enhancing power quality to ensure an efficient and uninterrupted energy supply. Ensuring a stable and high-quality power supply is crucial for both the grid's reliability and the efficient operation of EVs. Consequently, the need for effective strategies to mitigate these power quality concerns becomes imperative [14].

This review delves into the critical role of power quality enhancement in microgrids, particularly concerning the charging infrastructure for grid-connected electric vehicles. The proliferation of EVs has reshaped the traditional power grid dynamics, creating a complex interplay between energy supply, distribution, and consumption. As EVs draw significant power during charging, their connection to microgrids requires sophisticated measures to mitigate potential disruptions to overall grid stability and ensure seamless operation. This review explores the multifaceted aspects of power quality within microgrids, encompassing voltage stability, frequency regulation, harmonics mitigation, and overall grid resilience. It delves into the diverse methodologies, technologies, and control strategies employed to address power quality issues, specifically tailored to accommodate the demands of EV charging infrastructure. Examining various control techniques, power electronics solutions, and intelligent energy management systems, this review aims to dissect the methods utilized to optimize power quality in microgrid settings supporting EV charging [3].

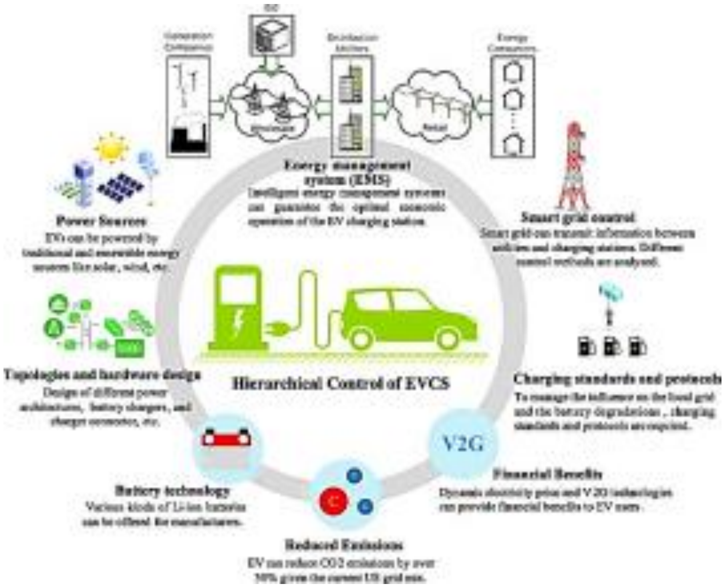


Fig. 1. Road Map of Electric Vehicle Charging Station

It aims to explore and analyse a spectrum of cutting-edge techniques designed to enhance power quality in microgrid-connected EV charging stations. Advanced control algorithms, such as model predictive control or fuzzy logic, offer precise management of power flow and grid stability. Energy storage systems (ESS), including batteries and supercapacitors, emerge as potent tools for buffering power fluctuations and optimizing grid performance. Additionally, active and passive filtering technologies play a pivotal role in eliminating harmonics and ensuring voltage stability. Furthermore, the integration of smart grid technologies offers real-time monitoring, fault detection, and adaptive control mechanisms, contributing significantly to maintaining power quality standards. However, the integration of EV charging stations into microgrids brings its own set of challenges, including bidirectional power flow management and the evolution of vehicle-to-grid (V2G) capabilities, which necessitate innovative solutions [4].

In India, various renewable energy sources are instrumental in improving power quality in microgrid connected electric vehicle (EV) charging stations. These sources contribute to a more sustainable and reliable power supply while mitigating power quality issues. Solar PV systems are widely adopted in India for power generation. They can be integrated into microgrids serving EV charging stations to provide clean energy, reduce dependency on the main grid, and stabilize power supply. Wind turbines are another prevalent renewable energy source in India. When incorporated into microgrids, wind power contributes to the energy mix, especially in areas with favourable wind conditions, reducing reliance on conventional power sources. Although less common in microgrids due to specific location requirements, hydropower can be integrated into certain regions of India, providing consistent and reliable renewable energy to stabilize microgrid operations. Biomass and biogas technologies utilizing organic waste materials can generate electricity. These sources can contribute to the energy mix and help in diversifying renewable energy sources in microgrids. Combining multiple renewable sources, such as solar-wind or solar-hydro, in hybrid systems offers increased reliability and power generation stability, minimizing the intermittency associated with individual sources [5].

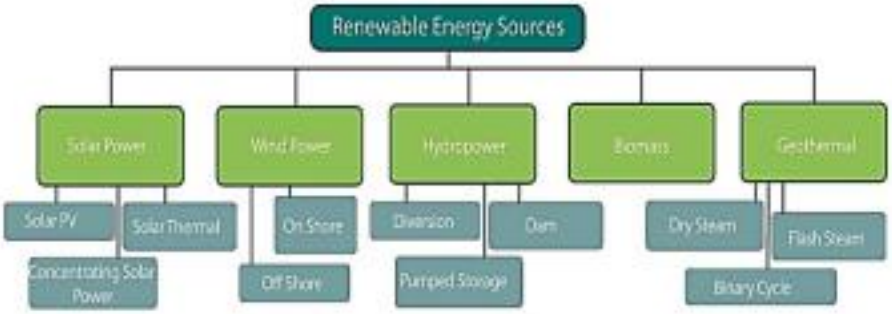


Fig. **2**. Promising Renewable Energy Sources

These renewable energy sources, when properly integrated into microgrid-connected EV charging stations, contribute to a more sustainable and resilient power supply. They help mitigate power quality issues by providing cleaner energy, reducing reliance on fossil fuels, and enhancing the stability and reliability of the microgrid, thereby supporting the growth of electric vehicle infrastructure in India [5].

This comprehensive review intends to delve into each of these power quality enhancement techniques, highlighting their functionalities, strengths, and limitations. Real-world case studies and experimental results will be presented to showcase the practical efficacy and implications of these methods in ensuring a robust and sustainable microgrid-connected EV charging infrastructure. Ultimately, this exploration aims to contribute to the advancement of power quality enhancement methodologies, enabling reliable and efficient operations in the evolving landscape of EV charging within microgrids. This study will discuss the existing challenges, emerging trends, and potential research avenues for enhancing power quality in microgrids, thereby contributing to the development of a sustainable and efficient energy ecosystem capable of supporting the expanding network of grid-connected electric vehicle charging infrastructure.

II. POWER QUALITY CHALLENGES IN MICROGRIDS:

The study emphasizes the importance of maintaining PQ in the electrical power system to provide end customers with an effective and dependable energy supply. The ideal role of the electrical grid is to provide consumers with an ideal voltage supply. The ultimate goal of the power supplier is to produce and supply the perfect voltage and current, which are both single-frequency sine waves at nominal levels with constant amplitude and frequency. The voltage and current must also be in synchronization [6]. This includes equipment manufacturers, facility designers, standards bodies, and suppliers of generation, transmission, and distribution in addition to end users. The equipment linked to the electrical grid is one of the many elements that influence PQ. Due to the substantial use of power electronic equipment in microgrids and RES-based power systems, their PQ is especially sensitive. PQ disturbances can result from transitions, voltage dips, swells, harmonics, imbalances, and oscillations.

Voltage Fluctuations: Voltage fluctuation is "a sequence of random voltage changes with magnitudes ranging from 0.95 to 1.05 p.u." or "systematic variations of the voltage waveform envelope." The word describes variations in the voltage amplitude that can happen once, repeatedly, arbitrarily, or regularly [7]. Figure 3 illustrates an example of voltage fluctuation in an arc furnace operating. Variable loads or generation could be the source of voltage fluctuation [8]. Moreover, abrupt grid disruptions that result in notable voltage swings might be caused by short circuits, transmission line problems, or equipment failures; depending on how serious and what kind of fault these disturbances are, voltage dips or spikes may result [9]. Variations in voltage inside the microgrid may result from sudden shifts in the demand for EV charging. High loads may impact the stability and functionality of linked equipment during concurrent EV charging sessions, resulting in voltage sags or swells.

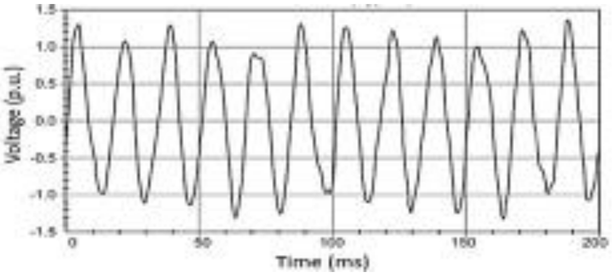


Fig. 3. Voltage fluctuation Induced by Arc Furnace

Harmonic Distortions: Harmonics are waveform distortions that occur as integer multiples of the fundamental frequency. Non-linear loads and devices bring on these distortions in normal operation, which are frequently made worse by power electronics. [8]. Regular operation of non-linear devices and loads typically results in the injection of current harmonics. DGs frequently use devices like pulse-width modulation (PWM) inverters, which are major generators of voltage harmonics because of their series connection with internal device impedances [7]. The Total Harmonic Distortion (THD) index commonly measures the severity of harmonic disturbance. The THD index is the ratio of the root-square of harmonic content to the nominal fundamental voltage (or current), expressed in percentage. This is shown in below equation, where Vh is the RMS value of the nth harmonic component of voltage (or current), and Vn is the RMS value of the nominal fundamental voltage (or current). Nonlinear loads associated with EV chargers can introduce harmonics into the grid. These harmonics, typically in the form of distorted currents or voltages, can degrade power quality, causing overheating in equipment and affecting the efficiency of power distribution.

Frequency Variations: The fundamental frequency of the power system deviates from its nominal value, known as power frequency fluctuations. There is an innate relationship between the generator rotational speeds inside the power system and the system's frequency, which is constant and steady-state [7]. The power system frequency is set by the balance between the generation capacity and the load, and any changes to this balance could result in minute fluctuations in frequency. Large and sudden changes in EV charging demand may cause frequency deviations within the microgrid. Frequency variations outside the acceptable range can impact the synchronization of grid components and affect the performance of sensitive equipment.

Unbalanced Loads: Unequal voltage magnitudes, current magnitudes, or phase angles across various phases are the hallmarks of imbalances, often known as imbalances [7]. A three-phase residential feeder's voltage imbalance trend is displayed in Figure 4. Particularly in systems with single-phase loads, voltage imbalances are generally less noticeable than current imbalances [7].

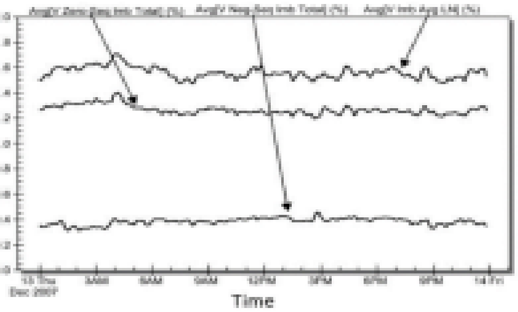


Fig. 4. Voltage Unbalance Trend for a Three-Phase Residential Feeder

Uneven distribution of charging among EVs or asymmetric load profiles can create unbalanced conditions in the microgrid. Unbalanced loads can lead to voltage imbalances and affect the overall power quality by causing uneven stress on the grid components.

$$\%VUF = \frac{\text{Negative sequence voltage component}}{\text{Positive sequence voltage component}}$$

Voltage Flicker: Power systems are susceptible to variations in voltage, and one common occurrence in low voltage (LV) and medium-voltage (MV) distribution networks is Rapid Voltage Change (RVC). Switching procedures that negatively impact equipment functioning are typically linked to RVCs [10]. Flicker, characterized as the "impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time," is the primary effect of RVC. Rapid changes in charging loads or variations in renewable energy sources can cause voltage flicker. This fluctuation in voltage perceived by the connected devices can lead to disruptions or disturbances in their operation.

Grid Instabilities: The grid may become unstable due to variations in frequency and voltage since solar energy is sporadic, and its generation is unpredictable depending on weather and time of day. The fluctuation in renewable energy sources is one of the primary reasons for grid instability in integrating renewable energy. The weather and daily cycles affect wind and solar output, unlike conventional power facilities that can be managed and changed to match demand [11]. Sudden changes in power demand or integration of intermittent renewable energy sources without proper control mechanisms can lead to grid instabilities, affecting overall power quality and system reliability.

Electromagnetic Interference (EMI): A vehicle's power converter is the main source of electromagnetic interference (EMI). EMI is produced by harmonics and by high-speed switching devices used by power converter systems to operate at high frequencies over a broad range. Electric motors must run at high power levels, similar to the power converter, as this could release electromagnetic emissions (EME) through impedance, which varies with frequency. An electric vehicle motor generates electromagnetic noise (EM noise) by using power inverters that operate at high speed, resulting in surge voltages at the terminals [12]. The charging process of EVs may generate electromagnetic interference that can affect nearby electronic devices and communication systems if not appropriately mitigated. By sorting out these power quality issues in microgrid-connected EV charging stations requires the implementation of advanced control strategies, appropriate filtering techniques, proper grid management systems, and smart charging protocols. Ensuring a stable and high-quality power supply to EVs while maintaining the reliability of the microgrid infrastructure is crucial for sustainable and efficient operation.

III. CHALLENGES ON VEHICLE-TO-GRID (V2G) OPERATIONS AND ISLANDED MODE

Vehicle-to-grid (V2G) charging technology is advantageous to energy providers and customers. It permits energy to move from an electric car's battery back to the power grid in a single direction. Thanks to this technology, we can get the most out of our current cars because EVs function as large-wheeled batteries supporting the grid. This is particularly crucial when the grid's energy comes from erratic renewable sources like solar and wind.

By 2030, there will be between 140 and 240 million electric cars on the road, translating to at least 140 million mobile energy storage devices with a combined storage capacity of seven trillion watt-hours. During Vehicle-to-Grid (V2G) operations and islanded mode in microgrid-connected electric vehicle (EV) charging stations, several power quality issues may arise due to the bidirectional power flow, disconnection from the main grid, and the dynamic nature of EV charging and discharging. Some of these power quality issues include:

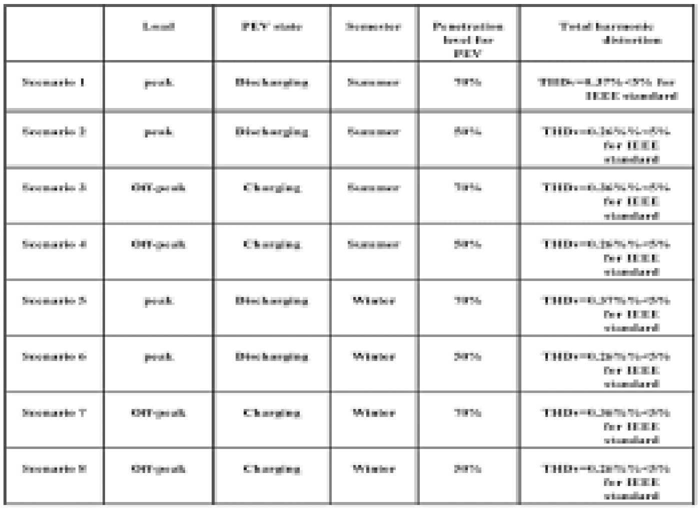
Table 1. Voltage Fluctuation Range of various EV Charging Scenario

EV Charging Scenario Voltage Fluctuation Range	
Slow AC Charging (Level 1)	±3%
Moderate AC Charging (Level 2)	±4%
Fast DC Charging (Level 3)	±5%
Simultaneous Multiple EV Charging	±6%
EV Charging with Voltage Regulators	±2%
EV Charging with Dynamic Load Management	±3%

Voltage and Frequency Instabilities: The voltage and frequency will be the focus of the investigation. The ability of the system to sustain equilibrium following a disturbance is the definition of stability. A disturbance occurs when the V2G is operational on the case study's distribution model, at which point the voltage and frequency are assessed. The voltage of the

Jordanian electricity system must remain constant between 220 volts and 50 Hz.

Table 2. THD Value at Various Scenarios of Load



	Load	PEV state	Semester	Penetration level for PEV	Total harmonic distortion
Scenario 1	peak	Discharging	Summer	70%	THDv=0.37%<5% for IEEE standard
Scenario 2	peak	Discharging	Summer	50%	THDv=0.26%%<5% for IEEE standard
Scenario 3	Off-peak	Charging	Summer	70%	THDv=0.36%%<5% for IEEE standard
Scenario 4	Off-peak	Charging	Summer	50%	THDv=0.26%%<5% for IEEE standard
Scenario 5	peak	Discharging	Winter	70%	THDv=0.37%%<5% for IEEE standard
Scenario 6	peak	Discharging	Winter	50%	THDv=0.26%%<5% for IEEE standard
Scenario 7	Off-peak	Charging	Winter	70%	THDv=0.36%%<5% for IEEE standard
Scenario 8	Off-peak	Charging	Winter	50%	THDv=0.26%%<5% for IEEE standard

The power quality, which also impacts equipment life, is the subject of another study. Equipment life is shortened, and maintenance requirements rise with unclean electricity. Voltage distortion is the main factor affecting power quality, and it will be assessed for each odd harmonic component before being assessed as a whole (THD) [14]. The technology of PEVs with dual orientations for generating and loading would impact frequency as the balance between load and generation determines it. A study is done on the frequency response to disturbances at the distribution model. Three feeders are defined for a switch event if they all have a fault and are disconnected at the same time. [14]. In V2G scenarios or islanded operation, sudden changes in power flow caused by EVs discharging energy back to the grid or islands can lead to voltage and frequency instabilities. These fluctuations may occur due to varying charging/discharging rates or sudden disconnections from the main grid [13].

Voltage Sags and Swells: As opposed to voltage sags (dips), voltage swells are less frequent and are typically caused by faults in the system. This causes the voltage level of the healthy phases to rise quickly. A sag (dip) is a drop in rms voltage or current at the power frequency that lasts for 0.5 cycles to 1 minute, falling between

0.1 and 0.9 pu. Swell a rise in rms voltage or current at power frequency lengths of 0.5 to 1 minute, to a value between 1.1 and 1.8 pu. [15]. In order to prevent sag or swell, Dynamic Voltage Restorers (DVRs) have been created to regulate the power supply to essential loads. DVRs do this by injecting a voltage of the necessary magnitude, phase angle, and frequency in series with the line and the load. Rapid changes in power flow during V2G operations or islanded mode can cause voltage sags or swells. When EVs switch between charging and discharging modes or when multiple EVs simultaneously feed power back to the microgrid, voltage variations can affect power quality [13].

Table 3. Voltage Sag and Swell Range of various EV Charging Scenario

EV Charging Scenario Voltage Sag Voltage Swell		
Slow AC Charging (Level 1)	-10% to -15%	+10% to +15%
Moderate AC Charging (Level 2)	-8% to -12%	+8% to +12%
Fast DC Charging (Level 3)	-12% to -18%	+12% to +18%
Simultaneous Multiple EV Charging	-15% to -20%	+15% to +20%
EV Charging with Voltage Regulation	-5% to 8%	+5% to +8%
EV Charging with Dynamic Voltage Control	-7% to -10%	+7% to +10%

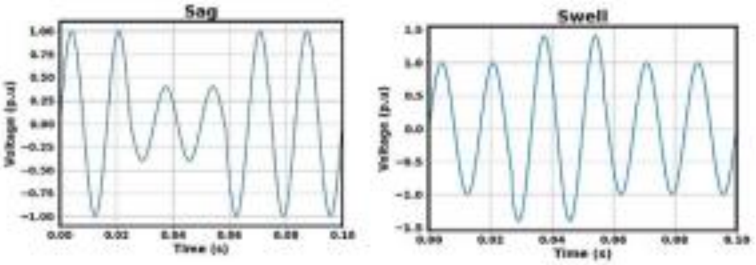
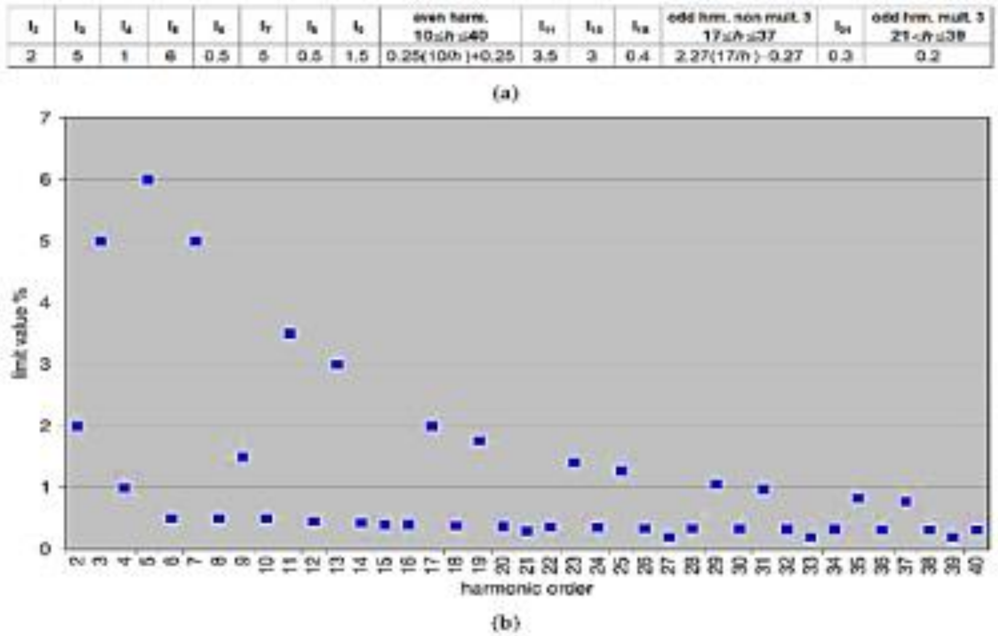


Fig. 5. Voltage Sag and Swell Waveforms

Harmonic Distortions: Generally, regulatory limits apply to distortion loads concerning overall harmonic distortion, emissions at higher frequencies, and harmonics first. A dichotomy exists whereby the acceptable voltage distortion levels for the electric network to which the load is linked are set, and each load is then assigned a specific amount of current distortion restrictions. The network characteristics and load mix assumed by this method are subject to change due to the growing amount of distorting loads that are now diffusely connected to LV distribution, such as EVs. The following examination highlights the more consolidated harmonic interval (up to the 40th harmonic) and goes over the various compatibility levels and emission limitations [17]. Bidirectional power flow from EVs introduces harmonics into the microgrid. In V2G operations, the switching converters in EV chargers and inverters can produce harmonics that degrade power quality, affecting other connected loads and equipment.



I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	even harm. $10 \le h \le 40$	I_{11}	I_{13}	I_{15}	odd hrm. non mult. 3 $17 \le h \le 37$	I_{21}	odd hrm. mult. 3 $21 < h \le 39$
2	5	1	6	0.5	5	0.5	1.5	0.25(10/h)+0.25	3.5	3	0.4	2.27(17/h)-0.27	0.3	0.2

(a)

(b)

Fig. 6. Harmonic Distortion Compatibility levels for LV Distribution Grid with a Prescribed Voltage THD Level of 11%: (a) Numeric Values, (b) Graphical Form.

Table 4. THD Value at Point of Common Coupling of various EV Charging Scenario

EV Charging Scenario THD at Point of Common Coupling (%)	
Slow AC Charging (Level 1)	8-12
Moderate AC Charging (Level 2)	10-15
Fast DC Charging (Level 3)	15-20
Simultaneous Multiple EV Charging	18-25
EV Charging with Advanced Filters	5-8
EV Charging with Passive Filters	7-10

Reactive Power Imbalance: In this research, DG units in islanding microgrids are controlled using an adaptive virtual impedance technique. The virtual impedance at the fundamental positive, fundamental negative sequence and harmonic frequencies are calculated based on transient real power changes. A transient control term is added to the traditional real power-frequency droop control to trigger tiny transient power changes. Reactive power, imbalance power, and harmonic power sharing mistakes in a microgrid can be adjusted steadily through the interplay between real power changes and the virtual impedance control [18]. V2G operations might lead to an imbalance in reactive power, affecting the overall power factor of the microgrid. Uneven distribution of reactive power among different EVs and loads can lead to inefficiencies and affect power quality.

Table 5. Reactive Power Imbalance Range of various EV Charging Scenario

EV Charging Scenario Reactive Power Imbalance	
Slow AC Charging (Level 1)	±5%
Moderate AC Charging (Level 2)	±7%
Fast DC Charging (Level 3)	±10%
Simultaneous Multiple EV Charging	±12%
EV Charging with Power Factor Correction	±3%
EV Charging with Reactive Power Compensator	±4%

Islanding Challenges: In an islanding operation, parallel DG units must appropriately share the load requirement. The reactive power-voltage magnitude droop control and real power-frequency control methods have been created to enable the power-sharing requirement without requiring any communications between DG units. To achieve precise reactive, imbalanced, and harmonic power sharing, a schematic compensation approach must be developed for an islanding microgrid with many nonlinear or imbalanced loads [18]. When the microgrid operates in islanded mode due to a grid outage or intentional isolation, challenges related to frequency regulation, load balancing, and stability arise. Varying EV charging/discharging patterns in islanded mode can exacerbate these challenges.

Transient Events: The terminology transient refers to a disturbance characterized with a high magnitude but short duration, typically between 50 ns and 50ns for both voltage and current. The two main categories of transitory phenomena are oscillatory and impulsive. According to [7], "sudden, non-power frequency change in the steady-state condition of voltage, current, or both that are unidirectional in polarity – either primarily positive or negative" describes an impulsive transient. These are characterized by peak value, ascent, decay, and duration time.

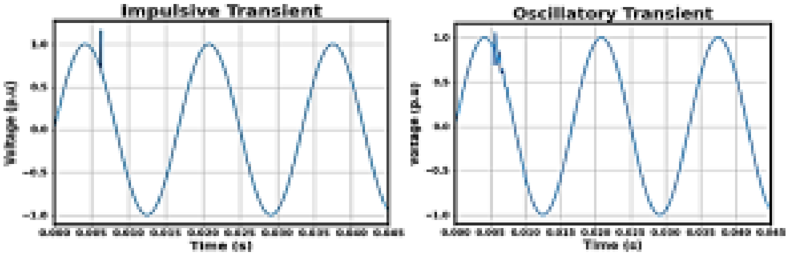
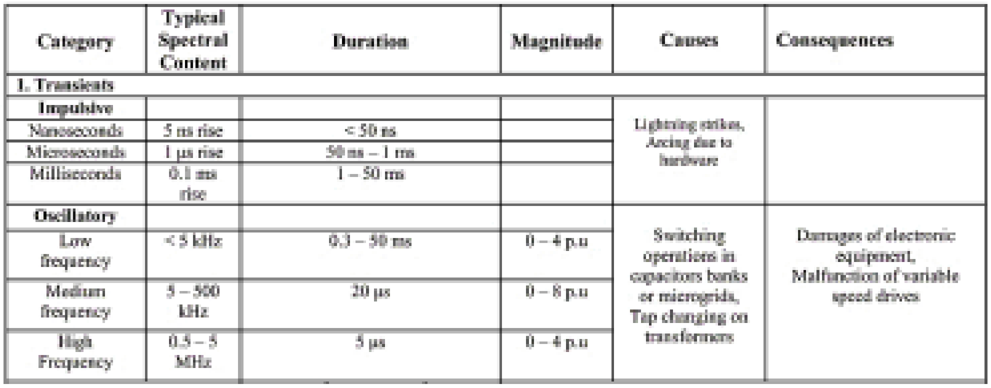


Fig. 7. Transient behaviour of the Microgrid

Most often, lightning strikes create impulsive transients, which, when they strike transmission lines, cause impulsive overvoltage [19]. Transient events, such as sudden connection/disconnection of EVs or switching operations during V2G transactions, can create transients in the microgrid, potentially causing voltage spikes or dips that impact power quality.

Table 6. Transient Phenomena on Microgrid



Category	Typical Spectral Content	Duration	Magnitude	Causes	Consequences
1. Transients					
Impulsive				Lightning strikes, Arcing due to hardware	
Nanoseconds	5 ns rise	< 50 ns			
Microseconds	1 µs rise	50 ns – 1 ms			
Milliseconds	0.1 ms rise	1 – 50 ms			
Oscillatory				Switching operations in capacitors banks or microgrids, Tap changing on transformers	Damages of electronic equipment, Malfunction of variable speed drives
Low frequency	< 5 kHz	0.3 – 50 ms	0 – 4 p.u		
Medium frequency	5 – 500 kHz	20 µs	0 – 8 p.u		
High Frequency	0.5 – 5 MHz	5 µs	0 – 4 p.u		

These power quality challenges during V2G operations and islanded mode requires sophisticated control strategies, advanced grid management systems, predictive control algorithms, and effective communication protocols. Proper coordination and control of power flow, voltage regulation, and frequency stability are essential to maintain high-quality power supply and grid reliability during these operating modes.

Table 7. Transient Duration Range of various EV Charging Scenario

EV Charging Scenario Transient Occurrence (Magnitude) Duration		
Slow AC Charging (Level 1)	+/- 5% of Nominal Voltage	<1 ms
Moderate AC Charging (Level 2)	+/- 8% of Nominal Voltage	<2 ms
Fast DC Charging (Level 3)	+/- 10% of Nominal Voltage	<3 ms
Simultaneous Multiple EV Charging	+/- 12% of Nominal Voltage	<5 ms
EV Charging with Surge Protection	+/- 4% of Nominal Voltage	<1 ms
EV Charging with Transient Filters	+/- 6% of Nominal Voltage	<2 ms

4. EXISTING POWER QUALITY IMPROVEMENT TECHNIQUES:

Power quality enhancement techniques for microgrid-connected electric vehicle (EV) charging stations encompass a range of strategies aimed at mitigating power fluctuations, harmonic distortions, and ensuring stable, high-quality power delivery.

1. Advanced Control Algorithms: Implementation of sophisticated control algorithms like Model Predictive Control (MPC), Fuzzy Logic Control, or Adaptive Control enables precise management of power flow within microgrids. These algorithms optimize energy distribution, voltage regulation, and frequency control, contributing to enhanced power quality. MPC algorithms predict system behaviour and make control decisions by solving optimization problems over a finite future horizon. In microgrid-connected EV charging stations, MPC can optimize power flow, manage energy distribution, and maintain desired voltage and frequency levels while considering dynamic changes in demand and supply [20]. Fuzzy Logic Control (FLC) employs linguistic variables and rule-based reasoning to regulate power quality parameters. Fuzzy logic controllers, adaptable to varying conditions, aid in maintaining stable voltage and frequency levels by adjusting control actions based on input data from sensors and grid conditions. Adaptive Control algorithms continuously adjust control parameters based on real-time system feedback. Adaptive control techniques enhance power quality by adapting to changing conditions, load variations, and system disturbances in microgrid-connected EV charging stations [21]. PID controllers adjust the control effort based on proportional, integral, and derivative terms. PID control can be applied to regulate voltage, current, or frequency in microgrids to ensure optimal power quality. Droop Control which is Commonly used in microgrids, adjusts the output of distributed energy resources (DERs) based on frequency deviation [27]. This method aids in maintaining grid stability and balanced power flow within microgrid-connected EV charging stations. Hierarchical Control strategies involve multi-level control hierarchies where different controllers manage various aspects of the system. They optimize power flow, voltage regulation, and frequency control by coordinating the actions of different components within the microgrid. Each algorithm has its strengths and applications. Implementing a combination of these algorithms tailored to specific power quality requirements is crucial in ensuring stable and reliable power supply to microgrid-connected EV charging stations. Their effectiveness lies in their adaptability to varying grid conditions, load changes, and real-time operational needs. These algorithms primarily focus on managing power flow, regulating voltage, and ensuring grid stability.

Table 8. Advanced Control Strategies

Controller	Advantage	Limitation	References
MPC	Delivers robust performance for nonlinear systems. Ability to operate at low switching frequency shows enhanced response to unreliability. Capability to control current with less harmonics.	Not adaptable to variation in system parameters. Inefficient load sharing. Mathematical calculations are difficult to compute.	[20]
Adaptive control	Simple implementation. Transient response is faster.	Adaption process is slow.	[21]
SMC	Robust performance during transient conditions and fluctuations. Minimum harmonics.	Complexity in design. Prone to chattering issues due to switching frequency.	[22]

KF	Accurate under frequency variations.	Difficulty in co-variance selection.	[23]
H infinity control	Minimum harmonics and enhanced performance. Robust control action and Tracking error is minimum. It can be implemented for both linear and unbalanced non-linear systems.	System response and dynamics are slower. It needs the aid of complicated systems and mathematical equations for understanding.	[24]
BSC	This control is used for stochastic non-linear systems.	With the increase of system order this control is more complex.	[25]
IC	High computational speed. High convergence rate.	Neural network complexity is proportional with harmonic component.	[26]

2. Energy Storage Systems (ESS): Energy storage system utilization is a key component of microgrids in conjunction with RESs. To support microgrids, individual loads put in microgrids or the utility grid, energy storage systems (ESS) are typically used to store excess electricity supplied by renewable energy sources (RESs) [28]. Energy storage devices are only sometimes implemented in the microgrids of review papers concerning supplementary power sources. Integrating ESS such as batteries, supercapacitors, or flywheels helps in buffering power fluctuations and providing ancillary services. ESS can balance loads, offer peak shaving, and aid in voltage stability, improving power quality in microgrids connected to EV charging stations [28]. ESS are categorized according to how energy is used in a certain way. Energy storage systems (ESS) fall into the following categories: mechanical, electrochemical, chemical, electrical, thermal, and hybrid. Additionally, these systems can be further categorized based on the materials and formation method [29].

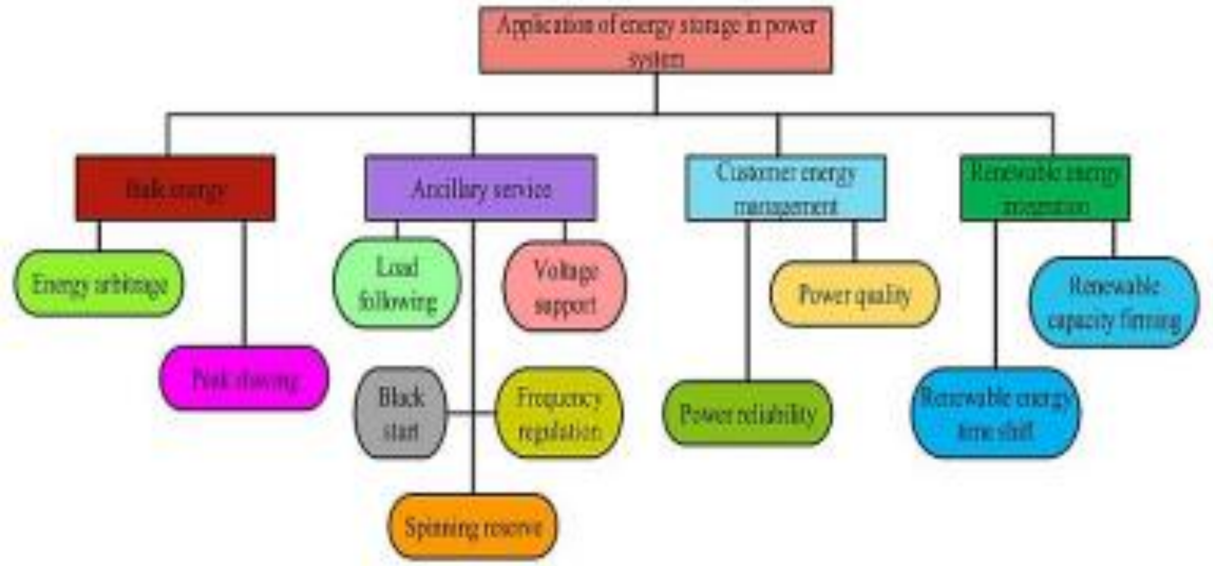


Fig. 9. Application Overview of Energy Storage System

Fig. 8. Distribution of different energy storage systems

3. Active and Passive Filters: Employing active filters (like active power filters or active harmonic filters) and passive filters (such as LC filters) assists in eliminating harmonic distortions and mitigating voltage fluctuations. These filters ensure a cleaner power supply to the charging stations and the grid, enhancing overall power quality. Passive filters are composed of passive components like resistors, capacitors, and inductors [30]. They are designed to mitigate specific harmonic frequencies and can be categorized as:

1. **Low Pass Filters:** These filters allow frequencies below a certain cutoff frequency to pass through while attenuating frequencies above that threshold. They are commonly used to filter out high-frequency harmonics in power systems.
2. **High Pass Filters:** Opposite to low pass filters, high pass filters allow higher frequencies to pass while attenuating lower frequencies. They can be used in certain applications to target specific harmonic distortions.
3. **Band Pass Filters:** These filters permit a specific band of frequencies to pass while blocking others. They are utilized to target and mitigate a narrow range of harmonic frequencies.

Passive filters are relatively simple in design, cost-effective, and suitable for addressing certain specific harmonic issues within a limited frequency range. However, their effectiveness might vary based on load variations and system changes.

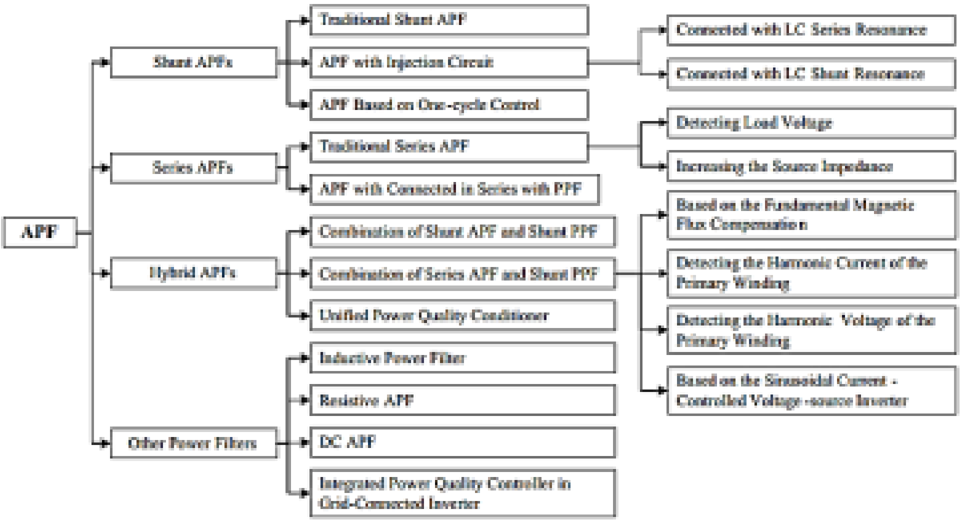


Fig. 10. Classification of Active Power Filter [37]

Active filters use power electronic devices and control systems to actively detect and compensate for harmonic distortions and other power quality issues. They offer more flexibility and adaptability compared to passive filters and can address a broader range of problems [50]. Voltage Source Converters (VSCs) filters are capable of injecting harmonic currents of opposite phase to cancel out undesired harmonics, effectively compensating for harmonic distortions. VSC-based active filters can be dynamically controlled to handle changing load conditions. Current Source Converters (CSCs) filters work by controlling the current injected into the system to counteract harmonic currents or other disturbances. They are often used to provide reactive power compensation and harmonics mitigation. Active filters offer higher efficiency, faster response times, and adaptability to varying load conditions. They are well-suited for complex power systems with non-linear loads and dynamic operating conditions. However, they are typically more expensive and require more sophisticated control mechanisms compared to passive filters. Both active and passive filters play essential roles in power quality improvement [31]. The choice between them depends on factors such as the nature of the power quality issue, system requirements, cost considerations, and the desired level of flexibility and control. Often, a combination of both types may be employed to achieve comprehensive power quality enhancement in a given power system.

Table 9. Types and Control Attributes of DFACTS Devices [31]

DFACTS Controller	Control Attributes	Type of Connection
DSSC (Distributed Static Series Compensator	Effective impedance of the transmission lines, Reactive power flow and voltage injection.	Series

DVR (Dynamic Voltage Restorer)	Voltage sag, Voltage swell, Harmonics, Notch, and Distortion by Non-linear load Currents.	Series
DSVC (Distributed Static VAR Compensator)	Voltage Stability and control, muffling of oscillations and Compensation of VAR’s.	Shunt
DSTATCOM (Distributed Static Compensator)	Transitory and dynamic stability, Fault current, Active and reactive power flow and muffling of oscillation.	Shunt
UPQC (Unified power quality conditioner)	Voltage sag, swell, harmonics, reactive power flow and voltage flickers.	Shunt-Series
DTCSC (Distributed Thyristor Controlled Series Compensations)	Current control, transitory and dynamic voltage, fault current and muffling of oscillations.	Shunt-Series
IPFC (Interline Power Flow Controller)	Active and Reactive power Supply, Voltage imbalance and fault current.	Series-Series

IV. Bidirectional Power Flow Management and V2G: Both active and passive administration are considered when operating a V2G network, whether centralized or decentralized. To manage bi-directional power flow between UG and EV, an aggregator operator (AO) is responsible for gathering data from the linked EVs across the network and sending out the necessary control signals. The AO schedules every linked EV based on load demand and generation, and energy loading and unloading are optimized according to the vehicles' battery capacity and charging/discharging schedule [32]. To address challenges related to bidirectional power flow in EV charging stations, Vehicle-to-Grid (V2G) technology allows EVs to not only draw power but also feed excess energy back to the grid. This bidirectional capability requires sophisticated control mechanisms to manage power flow effectively without compromising grid stability. Bidirectional power flow management allows for power to be sent back to the grid from distributed energy resources (DERs) or energy storage systems when there's excess generation [33]. This helps in stabilizing the grid by balancing supply and demand, especially during peak load times. With the increasing adoption of renewable energy sources like solar and wind, bidirectional power flow management facilitates the smooth integration of these intermittent resources into the grid. It allows excess renewable energy to be stored or redirected back to the grid when needed, reducing issues related to variability and intermittency [34]. By enabling power to flow bidirectional, the system can manage and balance loads more effectively. This includes shifting energy consumption to off-peak times, reducing strain during high-demand periods, and optimizing the utilization of available resources [35].

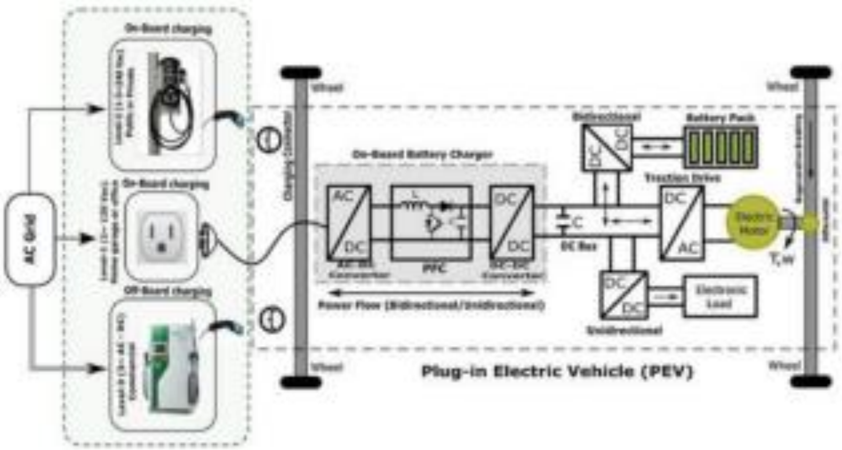


Fig. 11. Unidirectional and bi-directional power flow architecture in V2G technology

V2G technology enables electric vehicles (EVs) to not only draw power from the grid but also to supply energy back to the grid when connected. This technology offers several advantages for power quality improvement:

1. **Load Management:** EVs can serve as mobile energy storage units. During times of peak demand or grid instability, V2G-enabled vehicles can discharge stored energy to support the grid, acting as a distributed energy resource. This helps in load management and grid stability.
2. **Demand Response:** V2G systems can participate in demand response programs by adjusting charging or discharging based on signals from the grid operator. This allows for dynamic management of energy use and grid support during critical periods.
3. **Frequency Regulation:** EVs, when aggregated, can provide frequency regulation services by injecting or absorbing power based on grid frequency fluctuations. This helps in maintaining grid stability and improving power quality.

The synergy of these techniques plays a pivotal role in ensuring a reliable and high-quality power supply to EV charging stations within microgrids. Their integration and optimization contribute significantly to grid stability, reduced power fluctuations, and efficient utilization of renewable energy sources, fostering a sustainable and resilient power infrastructure for future transportation needs.

V. FACTS DEVICES IN POWER QUALITY IMPROVEMENT OF GRID INTEGRATED SYSTEMS

In this section, the authors Lee et al. [37][38] deliberated about voltage quality enrichment using FACTS devices. FACTS (Flexible AC Transmission Systems) devices play a significant role in enhancing power quality in microgrid-connected electric vehicle (EV) charging stations. These devices offer control capabilities to improve grid stability, regulate voltage, and manage power flow. Some prominent FACTS devices used for power quality enhancement include:

SVCs are used to regulate voltage levels by dynamically controlling reactive power flow. In microgrid with EV charging stations, SVCs help stabilize voltage fluctuations caused by varying loads, thereby enhancing power quality [37]. STATCOMs provide reactive power compensation and voltage control. They are utilized to support grid voltage stability and mitigate voltage fluctuations, especially in scenarios where EV charging stations cause intermittent load variations. UPFC is a versatile FACTS device capable of controlling both active and reactive power flow

[37]. It optimizes power flow, enhances voltage stability, and mitigates grid disturbances in microgrid-connected EV charging stations. Similar to STATCOM, a static compensator injects or absorbs reactive power to regulate voltage and improve power factor, ensuring stable voltage levels in microgrids affected by EV charging station dynamics [38]. Devices like Thyristor-Controlled Series Capacitors (TCSC) or Thyristor-Controlled Series Reactors (TCSR) are used to control the impedance of transmission lines. They aid in managing power flow and voltage stability, especially in scenarios where EV charging stations cause line impedance variations [38].

The DVR can reduce potential disruptions in voltage. Utilizing an injection transformer to inject the necessary voltage in series with the mains voltage, DVR is typically located between the load and the source in the distribution system to offer quick voltage assistance [45]. A fuzzy logic control and phase compensation DVR is created and tested in various failure scenarios, including voltage sags and short circuits. As is commonly known, sufficient quick active power recovery is necessary for frequency stability in the overall grid. In contrast, large reactive power absorption may negatively affect voltage recovery or cause a local voltage collapse. Active power recovery and the absence of excessive reactive power absorption are essential for system security. This contribution aims to show that these features can be provided for hybrid PV-wind generators tied to a grid system by the DVR using the suggested control strategy [45].

These FACTS devices offer dynamic control and rapid response capabilities, allowing for real-time adjustments to maintain power quality in microgrid-connected EV charging stations. By enhancing voltage regulation, reactive power compensation, and power flow control, FACTS devices contribute significantly to ensuring grid stability and reliable electricity supply to EVs while optimizing the overall performance of the microgrid system.

VI.OPTIMIZATION TECHNIQUES FOR POWER QUALITY ENHANCEMENT

These techniques aim to improve grid stability, manage power flow, and ensure reliable and high quality power delivery. Optimization techniques are employed for power quality enhancement in microgrid connected electric vehicle (EV) charging stations. Utilization of mathematical optimization models, such as Linear Programming (LP), Nonlinear Programming (NLP), Mixed-Integer Linear Programming (MILP), or Quadratic Programming (QP), to optimize power flow, energy distribution, and resource allocation within the microgrid [42]. These models ensure efficient utilization of resources while meeting power quality constraints. PSO is a heuristic optimization technique inspired by the social behaviour of birds or particles. It's used to optimize various aspects of microgrid operations, such as determining optimal charging schedules for EVs, minimizing power losses, or optimizing the placement and sizing of energy storage systems for power quality improvement [40]. GA mimics the process of natural selection and evolution to find optimal solutions to complex problems. In microgrid-connected EV charging stations, GA can be applied to optimize control strategies, determine optimal charging/discharging profiles of batteries in energy storage systems, or optimize resource utilization for enhanced power quality [42]. Employing machine learning algorithms such as neural networks, support vector machines, or reinforcement learning for predictive maintenance, fault detection, and real-time decision-making in microgrids. These techniques assist in identifying and mitigating power quality issues proactively. Techniques like Ant Colony Optimization (ACO), Simulated Annealing (SA), or Tabu Search (TS) are utilized to optimize various parameters within microgrid-connected EV charging stations [43]. They assist in finding near-optimal solutions for load balancing, grid stability, and power quality enhancement. Considering multiple conflicting objectives simultaneously, Multi-Objective Optimization (MOO) methods help in balancing trade-offs between different goals, such as minimizing losses, maximizing renewable energy integration, and ensuring power quality in microgrids [44].

The utilization of these optimization techniques allows for the development of efficient and adaptive control strategies, optimal resource allocation, and effective management of the complex interactions within microgrid-connected EV charging stations. These methods contribute to the enhancement of power quality while ensuring reliable and sustainable operation of the integrated systems.

VII. SMART CHARGING AND ADVANCED CONTROL STRATEGIES

Intelligent systems are increasingly utilized to enhance power quality in microgrid-connected electric vehicle (EV) charging stations. These systems leverage advanced technologies and algorithms to optimize grid operations, manage energy flow, and ensure reliable power supply. Some intelligent systems used for power quality enhancement in such settings include:

Predictive Maintenance Systems system use predictive analytics, machine learning, and IoT sensors to anticipate equipment failures or degradation. By predicting potential faults in advance, maintenance can be scheduled proactively, minimizing downtime and enhancing system reliability in microgrid-connected EV charging stations.

Artificial Intelligence (AI) for Fault Detection systems, including neural networks or machine learning algorithms, are employed for real-time fault detection and identification within microgrid systems. They rapidly detect anomalies or disturbances, enabling quick corrective actions to maintain power quality [51].

Smart Grid Management Systems integrate IoT devices, sensors, and data analytics to monitor and manage grid operations. They enable real-time monitoring of power quality parameters, facilitate automated control actions, and optimize grid performance, ensuring stable and high-quality power delivery to EV charging stations [51].

Energy Management Systems (EMS) utilizes optimization algorithms and predictive analytics to manage energy flow, storage, and distribution within microgrids. These systems optimize charging schedules for EVs, control energy storage systems, and balance supply-demand dynamics to enhance power quality and grid stability [43].

Distributed Control Systems (DCS) integrates intelligent control algorithms and distributed computing for coordinated control of multiple grid components. They enable precise control and coordination of various elements within microgrid-connected EV charging stations to ensure efficient and reliable power supply [51].

Cyber-Physical Systems (CPS) integrate physical components with computational and communication systems. These systems facilitate real-time monitoring, control, and coordination of grid components, ensuring optimal performance and power quality in microgrid environments [52].

VIII. FUTURE DIRECTIONS AND RESEARCH GAP

The research gap in "Power Quality Enhancement in Microgrid for Grid-Connected Electric Vehicle (EV) Charging Infrastructure" refers to areas within this domain that require further investigation or exploration due to limited existing research or unresolved issues.

1. Impact of EV Charging on Power Quality: Investigating the specific effects of EV charging on power quality within microgrids. Analysing the harmonics, voltage fluctuations, and power factor issues arising from EV charging activities and their impact on the overall power quality of the microgrid.
2. Optimal Integration of EV Charging Stations: Researching optimal strategies for integrating EV charging infrastructure within microgrids while maintaining or enhancing power quality. This includes studying placement, sizing, and control of charging stations to minimize adverse effects on the grid.
3. Control Strategies for Grid-Connected Charging Systems: Developing advanced control strategies for grid-connected EV charging systems within microgrids. This involves exploring smart charging techniques, load scheduling, and demand response mechanisms to mitigate power quality disturbances caused by charging EVs.
4. Power Electronics and Filtering Solutions: Investigating innovative power electronics and filtering solutions specifically tailored for EV charging infrastructure in microgrids. Developing improved converters, active filters, or other devices to address harmonic distortions and reactive power issues caused by EV charging.
5. Cyber-Physical Security Concerns: Exploring cybersecurity aspects related to EV charging infrastructure within microgrids. Assessing vulnerabilities, implementing secure communication protocols, and investigating potential cyber-attacks that might affect power quality and grid stability.
6. Grid-Interactive EVs for Power Quality Support: Researching the potential role of grid-interactive EVs as resources for power quality support within microgrids. Studying V2G (Vehicle-to-Grid) capabilities and their impact on enhancing power quality during charging and discharging cycles.
7. Integration of Renewable Energy and EV Charging: Investigating the synergies between renewable energy sources, EV charging, and power quality improvement strategies in microgrids. Analysing how the integration of renewables alongside EV charging impacts power quality and exploring optimized configurations.
8. Economic and Regulatory Considerations: Assessing the economic implications and regulatory frameworks associated with implementing power quality enhancement strategies for EV charging infrastructure within microgrids. Evaluating cost-benefit analyses, incentive mechanisms, and policy frameworks to encourage power quality improvements.

Addressing these research gaps would contribute to a more comprehensive understanding of the challenges and opportunities in enhancing power quality within microgrids that incorporate EV charging infrastructure, fostering the development of more efficient, reliable, and sustainable energy systems.

IX. CONCLUSION

The review has provided an in-depth analysis of the critical aspects surrounding power quality enhancement in microgrids concerning grid-connected electric vehicle (EV) charging infrastructure. The findings underscore the importance of addressing power quality issues arising from the integration of EV charging systems into microgrids, given their potential impacts on system stability, reliability, and efficiency. The gaps identified in existing research signal several potential avenues for future investigation. Focused studies on optimal control strategies, advanced power electronics, cybersecurity frameworks, and the role of grid-interactive EVs can significantly contribute to resolving these challenges.

Thus, improving power quality in microgrids accommodating EV charging infrastructure is a multifaceted endeavour. Addressing these challenges not only ensures grid stability but also supports the seamless integration of clean energy technologies, fostering sustainable and reliable energy systems for the future. This conclusion succinctly summarizes the key findings of the review, emphasizes the significance of the research, and suggests areas for future exploration in the domain of power quality enhancement within microgrids for grid-connected EV charging infrastructure.

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