International Journal of Mathematical, Engineering and Management Sciences
Vol. 9, No. 6, 1357-1381, 2024
https://doi.org/10.33889/IJMEMS.2024.9.6.073

Ram Arti Publishers

Optimal Control Strategies for Reliable Operation of Electric Vehicle Charging Stations under Fault Tolerant Scenarios

Swati Sharma
Department of Electrical Engineering,
Jamia Millia Islamia, New Delhi, India.
E-mail: swati.vashist19@gmail.com

Mohammad Amir
Department of Energy Sciences and Engineering,
Indian Institute of Technology Delhi (IITD), Delhi, India.
E-mail: md.amir@ieee.org

Majed A. Alotaibi
Department of Electrical Engineering, College of Engineering,
King Saud University, Riyadh, 11421, Saudi Arabia.
E-mail: majed.alotaibi.eeksu@gmail.com

Hasmat Malik
Department of Electrical Power Engineering, Faculty of Electrical Engineering,
Universiti Teknologi Malaysia (UTM), Johor Bahru, 81310, Malaysia.
&
Department of Electrical Engineering,
Graphic Era (Deemed to be University), 248002, Dehradun, Uttarakhand, India.
E-mail: hasmat@utm.my

Asyraf Afthanorhan
Artificial Intelligence for Islamic Civilization and Sustainability,
Universiti Sultan Zainal Abidin (UniSZA), Kuala Nerus, 21300, Terengganu, Malaysia.
&
Operation Research & Management Sciences,
Universiti Sultan Zainal Abidin (UniSZA), Kuala Nerus, 21300, Terengganu, Malaysia.
E-mail: asyrafafthanorhan@unisza.edu.my

Taha Selim Ustun
Fukushima Renewable Energy Institute, AIST (FREA),
National Institute of Advanced Industrial Science and Technology (AIST), Japan.
E-mail: selim.ustun@aist.go.jp

(Received on November 26, 2023; Revised on March 18, 2024 & May 21, 2024 & July 16, 2024 & July 31, 2024;
Accepted on August 14, 2024)

Abstract
With an increasing prominence of electric vehicles (*EVs*) in sustainable transportation, it demands a robust and steady charging infrastructure. The widespread adoption of *EVs* into the transportation ecosystem hinges on continuous and reliable operation of charging stations (*CSs*). This paper delves its focus on reliability and resilience of *EV* chargers using various fault-tolerant (*FT*) techniques. It also analyzes the *EV* chargers' failure scenarios such as hardware malfunctions and power outages which can disrupt the charging process. To evaluate these strategies, advanced *FT* algorithms and system reconfiguration protocols has been analyzed. Also, Total Harmonic Distortion (*THD*) act as key performance indicator which indicates the reduction from 60% to -40% with diminished current and voltage variations and enhanced grid stability. The extensive real-world research and simulations on

charging scenarios reflects the key performance metrics with 95% charging efficiency and fault recovery times of 0.8 seconds at 180 Volts. This research evaluates the compatibility and cost-effectiveness of these strategies with diverse *EV* models. Ultimately, the findings highlight the effectiveness and practicality of *FT* techniques for *EV* chargers providing valuable insights for infrastructure developers and ensures a reliable *EV* charging fostering consumer trust and accelerating the global transition to electric mobility.

Keywords- Electric vehicles, Fault-tolerance, Vehicular loaded chargers, Electric vehicle supply equipment, Off-board chargers.

1. Introduction

The escalating energy demand particularly in Northeast, Middle Eastern, Southeast Asian and European countries has led to the extensive exploitation of fossil fuels resulting in high pollutant emissions. To address these issues, the adoption of *EVs* over traditional vehicles has expanded significantly (Gaona-Cárdenas et al., 2022). The rise in pollutants and the surge in power demand from emerging *EV* charging can be managed by smart grids (*SGs*). Governments advocate for plug-in *EVs* (*PEVs*) as an appealing option to reduce CO_2 emissions, urban smog and other environmental interferences (Kim et al., 2020). Consequently, the automotive market analysis predicts that *EVs* will hold a significant 30% market share by 2030. The progress of *EVs* is critically dependent on battery technology with pressing concerns about cost, weight, charging speed and battery longevity (Pradeep et al., 2023). Beyond electrochemical and material challenges battery module performance is influenced by design, packaging and charging characteristics. The relationship between charging duration, battery life and charger characteristics are substantial. Battery mounts can be broadly categorized as off-board and on-board with the capability for unidirectional or bidirectional power flow (Ali and Sharma, 2022). Unidirectional charging simplifies grid connection while bidirectional chargers enable power infusion back into the grid (Zakaria et al., 2016). Off-board chargers are typically located in dedicated *CSs* offering robust power transfer but incurring higher infrastructure costs. Numerous charger designs and control strategies are explored in existing literature (Park et al., 2021). On-board chargers (*OBCs*) reduce the *EV* charging infrastructure expenses which are directly connected to the mains and they are constrained by the factors like size, cost and weight of an *EV*. The integrated *OBCs* have emerged as an operational thrust component with practical considerations during *EV* charging includes insignificant torque fluctuations and marginal winding adjustments (Karimi et al., 2008; Zhou and Tang, 2019).

Vehicular loaded chargers (*VLCs*) integrated with *FT* techniques has been extensively studied in the literature which focus on improving the resilience and reliability of electric vehicle charging stations (*EVCSs*) during faulty conditions (Amir et al., 2024). Malik et al. (2023) discusses various *VLCs* based fault detection algorithms which are designed to ensure uninterrupted functionality of the system by isolating and identifying faults during continuous operation. *FT* strategies enable *EV* chargers to sustain optimal performance during faulty conditions so that *EV* chargers work smoothly. Further, Zuo et al. (2021) examines the fault diagnosis methods for *VLCs* by emphasizing on modular design configuration that reduces the effect of faults on *EV* charging performance. Through experimental and simulation studies, the practicality and effectiveness of *FT* techniques showcases their ability to minimize the downtime and intelligent monitoring of maintenance costs. Thus, it promotes the continuous and safe operation of *VLCs* with *FT* techniques. Sharma et al. (2022) discusses about significant role of *FT* techniques which ensures the safety of *VLCs* by enhancing the reliability of *EV* power converters and *EV* motors. Thus, these are the important factors in widespread adoption of *EV* charging infrastructure. The various *EV* control methods explored by the researchers mitigates the effect of faults at electric vehicle supply equipment (*EVSEs*) which includes voltage source converters (*VSCs*), model predictive control (*MPC*) and adaptive control. Collectively, these studies aim to strengthen the robustness, resilience of *EV* charging infrastructure and ensures the reliability of *EV* charging services (Jin et al., 2017; Zhang et al., 2024).

EV motors cover a range of permanent magnet synchronous machines (*PMSMs*), switched-reluctance motors (*SRMs*) and induction motors (*IMs*) (Zhang et al., 2024). *PMSMs* plays a pivotal role in battery electric vehicles (*BEVs*) by directly influencing the *EV* overall performance and its speed. When *IMs* and *OBCs* are integrated, they offer various advantages such as cost-effectiveness and reliability to the system. This helps *PMSMs* in delivering a superior efficiency. Due to *FT* systems, the *SRMs* emerge as a convincing choice for *OBCs*. The factors that influence the selection of *EV* motors during *EV* charging are torque generation capabilities and hardware adaptation requirements. Similarly, the multi-phase machines are preferred for their ability to reduce system faults and per-phase ratings which contributes to a more efficient and robust *EV* charging process. During *EV* charging process the motors must curtail the torque generation which require complex, costly and robust controllers and inverters. In *PMSMs*, the configuration of fractional slot concentrated winding (*FSCW*) offers different challenges and advantages related to rotor losses, flux distribution and mechanical vibrations (Ke et al., 2024). This manuscript broadly examines the performance evaluation of integrated *VLCs* for *EVs* by classifying them based on *FT* techniques, power supply and various charger types concerning technical challenges, advantages and constraints. Existing topologies and *FT* methods are compared based on efficiency, configuration and isolation of the *VLCs*. The concept of diverse *FT* methods is categorized into different levels: grid, module, switch, system and measurement as illustrated in **Figure 1**.

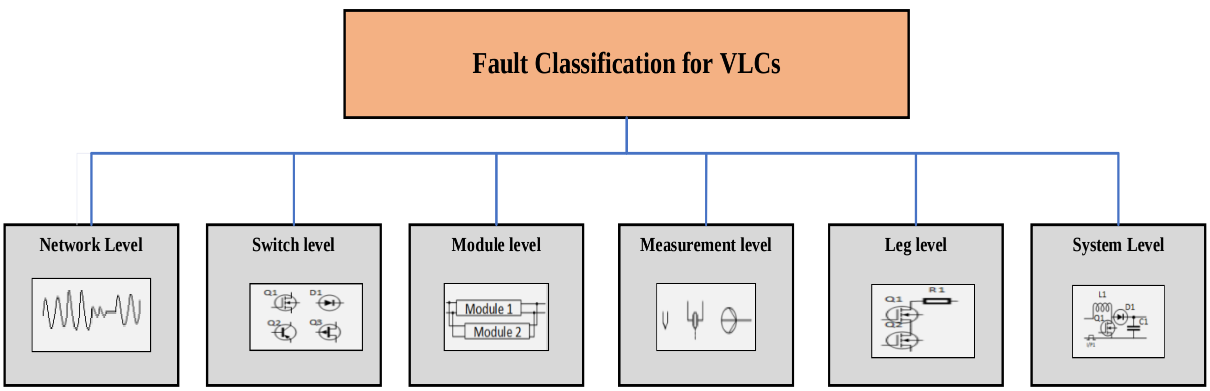

Figure 1. Classification of VLCs fault tolerant techniques.

Thus, the *FT* techniques can be further classified as- a switch-level *FT* technique which identifies short or open circuit scenarios within power semiconductor devices such as diodes, silicon-controlled rectifiers (*SCRs*), *MOSFETs* or *BJTs*. A leg-level *FT* technique addresses short or open circuit scenarios affecting one or more components disrupting or disabling the power conversion process of an *AC* phase. Module-level faults involve issues within sections (*modules*) of cascaded multilevel converters (*CMCs*) or modular multilevel converters (*MMCs*), where module failure necessitates reconfiguration of the remaining modules to maintain uninterrupted operation. Cascaded or paralleled configurations employ multiple simpler power electronic converter (*PEC*) devices interconnected with other power electronic devices where system-level failures refer to the malfunction or damage of one such converter. Measurement-level faults occur in current or voltage sensors degrading system performance and potentially causing severe malfunctions in *PECs*. Grid or network-level faults are associated with power quality problems including phase unbalance, sags and swells which can damage *PECs* or *OBCs*.

Figure 2 categorizes various fault diagnosis methods for *VLCs* aiming to enhance their efficiency. Furthermore, it provides an in-depth analysis of the current *EV* battery power levels, charging infrastructure and battery charger routines. It assesses battery bases, control strategies, charging scenarios and fault diagnosis criteria. Fault diagnosis for *EV* battery chargers involves identifying and analysing abnormalities or malfunctions in the charging system such as voltage fluctuations, current irregularities or temperature glitches. Comprehensive monitoring and analysis of parameters like voltage, current and temperature allow fault diagnosis systems to detect potential issues ensuring the safety and reliability of the *EV* charging infrastructure. Upon fault detection, these systems alert operators or users enabling prompt action through automated responses, system shutdowns or manual intervention thereby minimizing downtime and ensuring continuous operation of the *EV* charging infrastructure.

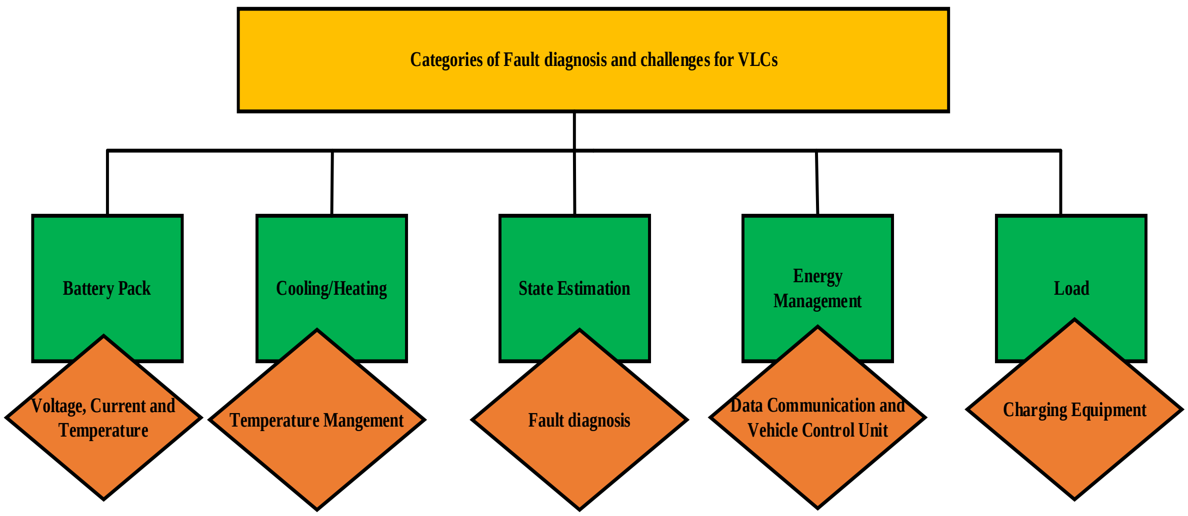

Figure 2. Categories of faults diagnosis and the challenges for VLCs.

Also, the paper presents an advanced classification of faults in *PECs* for onboard charging along with their corresponding tolerance schemes. A comparative analysis of the most relevant *FT* strategies is performed to evaluate potential novel techniques and identify future research directions. The selection of *FT* techniques in this study is based on the onboard charging capabilities of *PECs* for both *AC* and *DC* drive systems. In addition, this paper enhances *EV* charger reliability by evaluating *FT* techniques for scenarios such as hardware faults and power outages. These strategies include component redundancy, intelligent fault detection and system reconfiguration which reduce total harmonic distortion (*THD*) from 60% to- 40% reaching 95% charging efficiency and enable a recovery time of 0.8 seconds at 180 V. The effectiveness and cost-efficiency of these techniques ensure seamless operation of *EVCS* fostering consumer trust and accelerating the transition to electric mobility.

The manuscript is organized into the following sections: Section 2 outlines the classifications of *EV* charging, the infrastructure for *EV* battery chargers and the various levels of *EV* charging. Section 3 discusses *FT* standards and the different control strategies for *VLCs*. Section 4 presents a comparison of different operational modes for *VLCs*. Finally, conclusions are drawn in Section 5 followed by references.

2. Electric Vehicles Charging Arrangement

Battery chargers are pivotal in advancing the progress of *EVs* as the lifespan and charging time of batteries which are closely tied to the attributes of the chargers. For a battery charger to be effective and dependable it must possess qualities such as high-power density, affordability, compactness and lightness. Its operation relies on various factors including modules, control systems and switching methods. Various control algorithms can be applied for *EV* charging using conventional regulators and multiple circuits depending on factors such as pricing, rating and converter types (Musavi et al., 2011). To minimize any negative effects on power quality, the *EV* mount draws electric current with minimal distortion and maintains a high-power factor, maximizing the actual power drawn from the utility source. *EV* mounts are typically designed to comply with standards like IEEE1547, SAE-J2894, IEC1000-3-2, and the U.S. National Electric Code (*NEC*) 690 (Singh et al., 2003) which impose limits on permissible harmonic and direct current infusion into the grid. Contemporary *EV* battery chargers often use a boost converter for active power factor correction (*PFC*). In some configurations, the boost stage follows the *AC* input conversion into *DC* output using a specialized diode bridge. An alternative method known as the bridgeless boost *PFC* architecture retains the boost configuration while eliminating the input bridge rectifier, though this strategy might result in a higher prevalence of electromagnetic interference (*EMI*) (Manjrekar et al., 2000).

Similarly, an interleaving method has been proposed for battery charging to address issues related to ripple. By eliminating ripples at the output, the interleaved boost converter reduces the stress on output capacitors and benefits parallel-connected semiconductors. However, it faces heat management challenges with the input bridge rectifier similar to the standard boost topology which limits its use to power levels up to 3.5 kW. For higher power levels, a new bridgeless interleaved arrangement was introduced effectively controlling system ripples. Multilevel converters are well-suited for level 3 *EV* chargers due to their smaller size, lower switching frequency and reduced strain on devices. They allow for the use of more affordable and smaller filters. However, the increased complexity and additional components drive up the total cost and require more sophisticated control circuitry. Most *EVs* now utilize single-phase onboard chargers through level 3 charging systems employing three-phase (3-ϕ) bidirectional converters as described by Abraham et al. (2021).

2.1 Electric Vehicle Battery Charger Infrastructure and Platforms

EV battery charging encompasses a wide spectrum of critical factors including power capacity, charging duration, location, cost considerations, equipment specifications and their broader implications for the electrical grid. The arrangement of the charging setup and *EVSE* holds profound significance due to various key considerations. These include the timing of charging sessions, the development of distribution networks, the extent of coverage, demand management policies, standardization efforts for *CSs* and the necessary regulatory framework (Subotic et al., 2016a). The presence of charging infrastructure plays a pivotal role in mitigating the need for substantial onboard power loading by reducing overall costs. Essential elements of *EVSE* as outlined by Sharma and Ali (2023) include *EV* charging cables, public or home-based charging stands, power outlets, attachment plugs, vehicle connectors and safety features. The two main configurations are wall-mounted or base-encased arrangements and specific cable sets. These configurations vary by location and nation based on voltage standards, electrical frequency, grid connections and transmission requirements. Most *EV* owners are likely to charge their vehicles overnight at home-based chargers. According to the Electric Power Research Institute (*EPRI*) (Subotic et al., 2016b), level 1 and level 2 charging options are the most popular. The levels of charging are described in **Table 1** followed by its description.

Table 1. Levels of power charging and their applications.

Charger type	Power level (kW)	Application/Usage
Level 1 Charger	Up to 2.4 kW	Home charging, slow overnight charging
Level 2 Charger	3.7 kW to 22 kW	Residential, public charging, workplaces
Level 3 Charger	50 kW to 350 kW	Fast charging stations, commercial use
Level 4 Charger	Over 350 kW	Ultra-fast charging, high-power stations

2.1.1 Level 1 Charging

This is one of the most leisurely charging approaches. In the United States, it utilizes a standard 120 V/15 A single-phase (1-ϕ) grounded outlet exemplified by the NEMA 5-15R configuration. A standard J1772 connector is employed to connect to the *EVs AC* port. For residential or commercial use, this infrastructure benefits from off-peak rates often accessible during night-time hours. Reports indicate that the installation cost of a residential single-level charging infrastructure ranges from approximately $500 to $880 (Sharma and Ali, 2024). However, it is generally expected that Level 1 charging will ultimately be integrated directly into the vehicle.

2.1.2 Level 2 Charging

This level plays a fundamental role in providing dedicated remote charging facilities. This infrastructure can be integrated directly into the vehicle to eliminate the need for redundant power electronics. Level 2 equipment currently in use operates at 206 V or 260 V (up to 90 A, delivering 19.5 kW). For installations in public or residential areas specific hardware connection configurations may be required (Thimmesch, 1985; Lee and Sul, 1994). Certain *EV* companies like Tesla have pre-installed power circuitry requiring the appropriate socket for charging. Most American homes have 240 V Level 2 chargers which can fully charge an *EV* battery overnight. Level 2 technology charges a vehicle more quickly and has a standardized interface between the vehicle and the charger which owners usually prefer. It is common to integrate separate billing meters to accurately measure charging usage costs. A Level 2 charger costs between $500 and $2,500 for installation (Bai et al., 2017) with residential units typically costing around $2,150. An additional $3,000 is required for the Tesla Roadster charging system. The standard used in Level 2 charging has an SAE J1772 *AC* charge connector on top and a two-pin *DC* connector on the bottom enabling a single connection for *AC* and *DC* fast charging simultaneously.

2.1.3 Level 3 Charging

This is the fastest charging method representing a transformative leap in the charging landscape by offering the remarkable potential for swift *EV* charging in less than one hour. These high-speed chargers are commonly deployed at rest areas and urban refuelling points resembling the ubiquity of traditional gas stations. Level 3 chargers typically operate on a 490 V 3-ϕ circuit (Herrera et al., 2019) necessitating an off-board charger to ensure the controlled conversion of efficient *AC* to *DC* for *EV* charging.

AC charger connectors are used for Level 1 and Level 2 charging which are integrated within *EVs* while Level 3 charging is externally positioned. Collective *CSs* are expected to rely primarily on Level 2 and Level 3 charging serving as the go-to options for swift charging in public areas. Opting for lower charging power levels benefits utility providers by mitigating their impact on peak electricity demand. However, adopting high-power charging carries the risk of demand surges that could overwhelm local distribution infrastructure during peak usage periods (Sharma and Ali, 2024). Both Level 2 and Level 3 charging can contribute to increased transformer losses, voltage fluctuations, harmonic distortion and strain on the supply potentially affecting the lifespan, consistency, safety, operational efficiency and overall economic feasibility of emerging *SG* systems. Implementing controlled smart charging can help alleviate the wear and tear on conventional distribution equipment. The rising number of *EVs* necessitates a robust communication network and efficient control systems for public charging infrastructure.

2.2 Unidirectional and Bidirectional Chargers

When an *EV* has a unidirectional charger installed, the *EVs* battery draws power from the grid but cannot transfer energy back into it. These chargers typically feature bridges with filters and *DC* converters, composed of single-level systems to maintain cost-effectiveness, minimize weight, reduce volume and limit energy losses. Special transformers can be employed in scenarios requiring high-frequency isolation.

Unidirectional chargers offer simplified utility management of heavily loaded feeders due to their open control mechanisms. Ongoing research (Bukya et al., 2024) in single-directional charging aims to identify optimal charging practices that maximize benefits by analyzing their effects on distribution networks. With a significant portion of *EVs* and carefully managed charging currents, unidirectional chargers can meet most utility goals without incurring common issues such as increased costs, compromised performance and safety concerns.

Table 2 compares unidirectional and bidirectional chargers based on factors like power flow, *PFC*, charging speed, hardware complexities, cost, transformer specifications, efficiency and applications. On the other hand, bidirectional chargers are versatile devices capable of both *EVs* charging and discharging. This technology allows energy flow in both directions, enabling *EV* batteries to supply power back to the grid (*V2G*) and receive power from the grid (*G2V*). They play a crucial role in *V2G* and *G2V* operations facilitating energy storage and grid stabilization. By integrating bidirectional chargers, *EV* owners can contribute to grid flexibility and earn revenue through participation in demand response (*DR*) programs.

Table 2. Comparison of unidirectional and bidirectional chargers.

Characteristic	**Unidirectional charger**	**Bidirectional charger**
Power Flow	One-way (grid to vehicle)	Two-Collaborative (V2G and G2V)
Applications	Simple *EV* charging	V2G, Grid stabilization, Bi-directional power flow
Power Factor Correction	Generally, not required	Often required for grid compliance
Charging Speed	Slower (level 1 or 2)	Faster (level 2 or 3)
Complexity and Hardware	Simplified control, fewer components	More complex control, additional components
Efficiency	Typically, high for unidirectional chargers	Efficiency may vary based on bidirectional functionality
Transformer Requirements	Rarely uses isolation transformers	May require isolation transformers for safety
Impact on Grid	Limited impact on grid power quality	Can impact grid power quality due to bidirectional power flow
Cost Considerations	Generally cost-effective	Costs may be higher due to added features
Battery Degradation	Less frequent cycling, lower risk	More frequent cycling, may increase battery degradation
Commercial Adoption	Widely adopted for *EV* charging	Gaining traction, especially in V2G and grid applications

A distinctive bidirectional charger consists of two primary levels: a dynamic grid-linked *AC-DC* converter that ensures power factor improvement and a bidirectional *DC-DC* converter responsible for regulating battery current as detailed in references (Thimmesch, 1985; Salkuti et al., 2023). These chargers can be configured in either non-isolated or isolated circuit setups. In charging mode, they draw a sinusoidal current with a specific phase angle to efficiently regulate both reactive and total power. **Figure 3** illustrates the power charger which is designed to return the current in sinusoidal form using a transformer during discharging and power switches to minimize losses and enhance efficiency in accordance with the concepts presented in references (Thimmesch, 1985; Sharma and Ali, 2024).

Bidirectional chargers offer a versatile range of functionalities that support both *G2V* and *V2G* scenarios playing a crucial role in power stabilization. A non-isolated bidirectional two-quadrant charger is characterized by its direct control circuitry using two switches. However, it has several disadvantages including the presence of two high-current inductors that can be large and expensive which can either reduce or boost power in a single direction. On the other hand, an isolated bidirectional dual-active bridge charger is known for its high-power density and rapid control capabilities, though it may incur higher costs due to the increased number of components.

Previous research (Salkuti, 2023) has focused on bidirectional power flow challenges and its widespread adoption. These challenges include battery degradation due to frequent cycling, the added cost associated with bidirectional chargers, metering complexities and the improvements required for distribution systems. Consumers demand energy assurance by confirming the predictability and sufficient charging levels needed for driving. The effective functioning of bidirectional power necessitates comprehensive safety procedures including anti-islanding protection and addressing concerns related to the interconnection of power electronic devices.

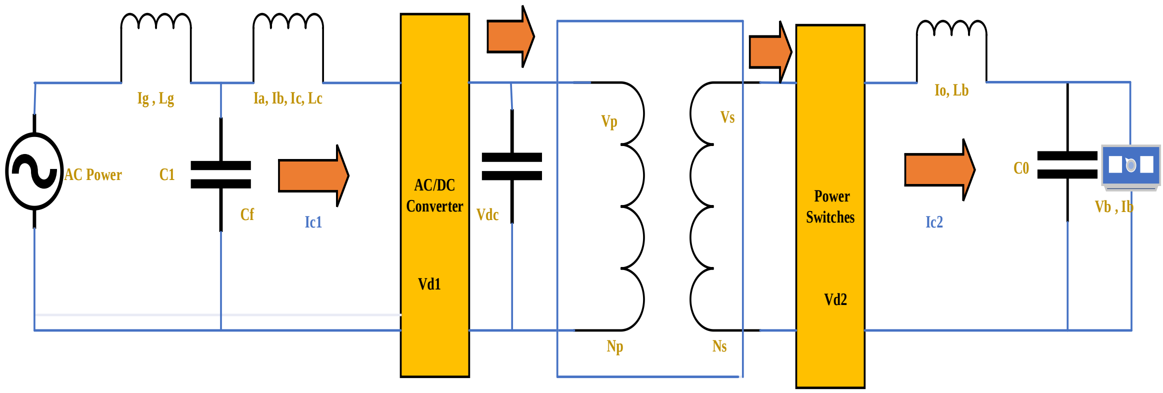

Figure 3. Schematic diagram of EVs power charger.

2.3 On-board and Off-board Electric Vehicle Chargers

EV owners benefit from incorporating an on-board charger within their vehicles providing the flexibility to recharge whenever a suitable power source is accessible. However, the capacity of these *OBCs* is typically restricted to level 1 charging due to constraints such as weight, spatial limitations and cost considerations as detailed in references (Jin et al., 2017; Zuo et al., 2021). To overcome these challenges and enhance charging efficiency resonant circuits for *EV* batteries have proven to be valuable assets. A practical example is the single-direction full-bridge resonant circuit which exemplifies the on-board level 1 charger illustrated in **Figure 4** discussing on-board (internal) and off-board (external) charging. Standard power ratings for *EVs* exceed 35 kW for off-board charging solutions necessitating power electronics structures that result in additional costs. Off-board charging methods also introduce disadvantages including increased susceptibility to issues and contributing to urban clutter.

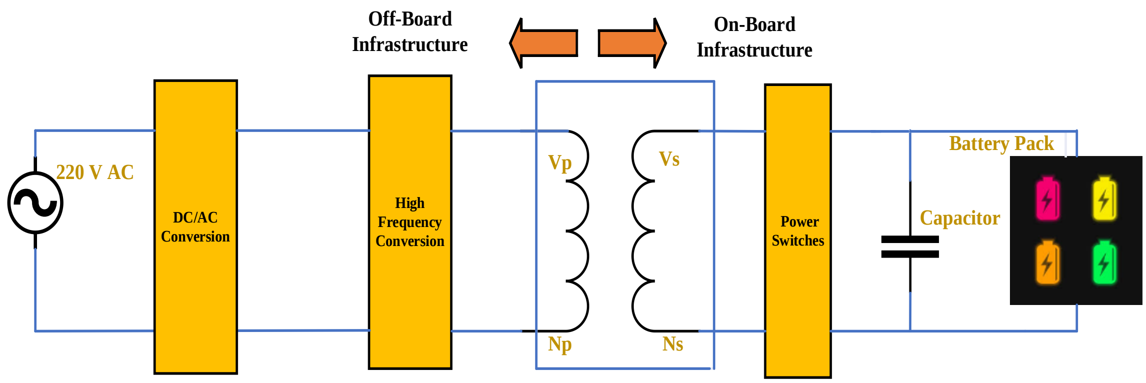

Figure 4. Schematic diagram of on-board and off-board charger.

2.4 Integrated On-board and Off-board Electric Vehicle Chargers

Thus, addressing the critical factors such as mass, price and capacity has led to the innovative concept of incorporating the charging utility directly into the power-driven system. This approach is well-documented in references (Karimi et al., 2008; Amir et al., 2023) with its roots dating back to 1985 (Thimmesch et al., 1985) and further developments through a series of patents secured by Rippel and Cocconi in 1990, 1992 and 1994 (Kim et al., 2020). The integration of battery chargers is particularly effective when charging and traction operations occur at separate intervals. In an integrated charger setup motor windings perform dual functions as filter inductances or a secluded moderniser while the motor drive functions as a versatile bidirectional *AC-DC* converter.

One of the most remarkable benefits of this integration is its ability to support high-powered, cost-effective charging for level 2 and 3 chargers while maintaining unity power factor. The implementation of integrated chargers, however, poses challenges related to control complexity and the integration of external hardware. Ford Motor Company has adopted a linked motor and battery revive system cantered on an induction motor. **Figure 5** illustrates a non-secluded integrated charger with a split-winding *AC* machine which gains momentum using a symmetrical 6-ϕ machine and an isolation transformer for fast battery charging. This technology has found applications in various contexts including electric automobiles and two-wheeler vehicles.

Similarly, the one-motor with one-power converter topology is a simplified yet efficient configuration used in *EV* thrust systems streamlining both manufacturing and maintenance processes while maintaining performance standards as shown in **Figure 6.** In this setup, a single electric motor is paired with a power converter. This single-motor approach reduces system complexity, weight and cost making it an attractive choice for various *EV* models. It offers precise control over the motor's speed and torque enhancing overall drivability and energy efficiency. When the redundancy of multiple motor setups lacks in various aspects then it strikes a balance between its efficiency and performance. Thus, it provides a rational option for *EV* manufacturers for optimizing the powertrain designs.

The two distinct methodologies for incorporating *IMs* within *EVs* are isolated and non-isolated configurations. In non-isolated configurations, the power supply is directly connected to the *EV* motors by making it a cost-effective choice. Due to the absence of electrical disconnection, this setup may fall abruptly in meeting the safety standards. In isolated configurations, a galvanic isolation transformer has been utilized as a protective barrier between power source and motor which ensures compliance with safety requirements. For increasing the safety requirement and enhancing the system capability, the transformer can be used but it may increase the system cost and complexity.

The choice between *IMs* isolated and non-isolated configurations depends on safety constraints, application aspects and the anticipated level of electrical separation in *VLCs*. In *FT* systems, *VLCs* are crucial elements which enable continuous operation within *EV* charging infrastructure. Thus, the adaptive control algorithms, unidirectional *AC/DC* converters and bidirectional chargers when integrated with *FT* techniques detect and mitigate the faults by ensuring uninterrupted charging during emergency circumstances. This capability is essential for enhancing overall system reliability particularly in substantial applications such as *SGs* and transportation networks.

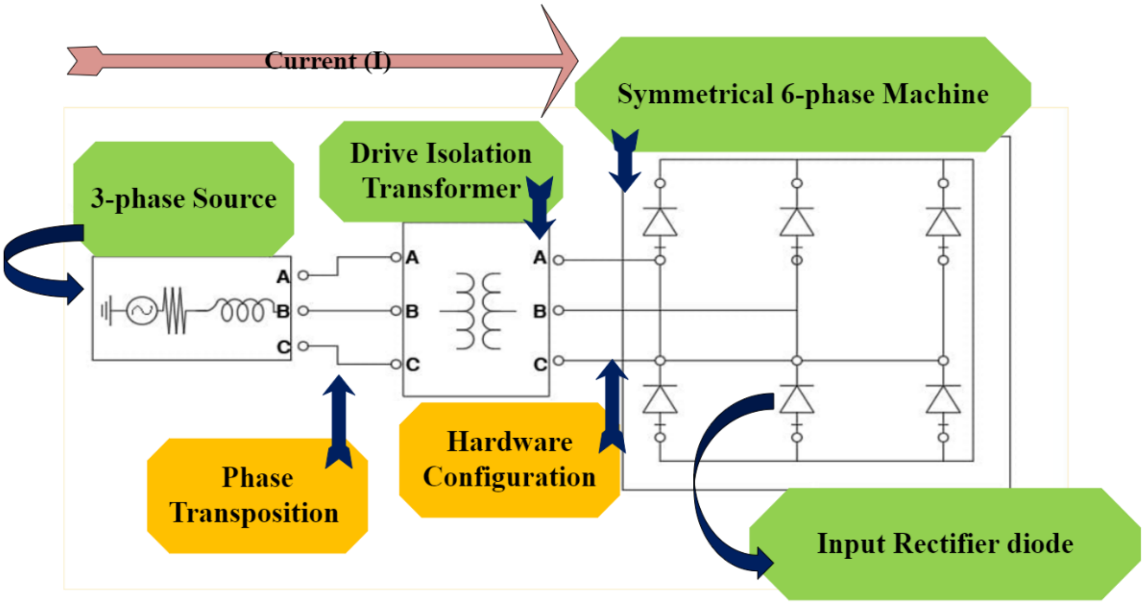

Figure 5. Schematic diagram of isolated symmetrical 6-ϕ machine.

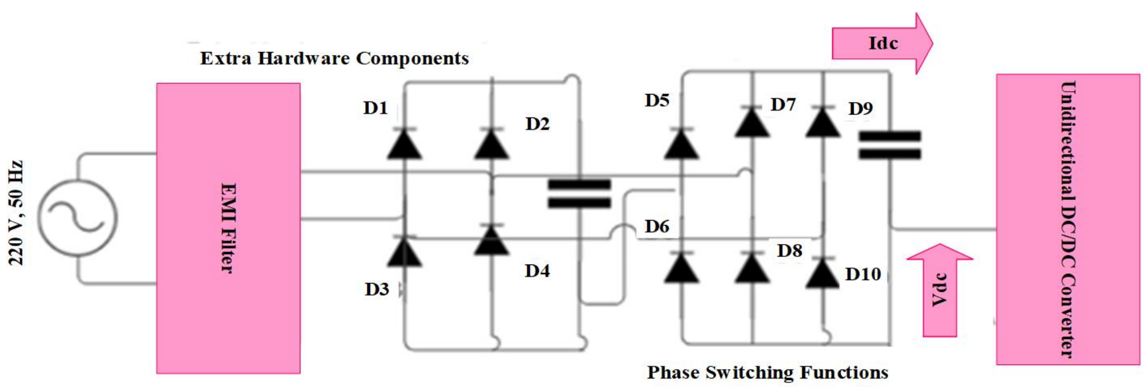

Figure 6. Representation of a discrete hardware components in unidirectional AC/DC converter.

3. VLCs Control Strategies and Fault-Tolerant Standards

Based on the control strategies and operational types of *VLCs*, the extensive utilization of *RERs* has been realized. The primary challenge lies in effectively controlling, monitoring and managing the current distribution across the entire *VLC* system. This study explores various control strategies including grid-level operation, module-level operation, switch-level operation, system-level operation and measurement-level operation each with its unique mechanisms for optimizing performance and reliability.

3.1 VLCs Configuration: Standards and Control Strategies

The various operational challenges for *VLCs* and the control methods for fault management in *EVs* are described as follows:

3.1.1 Grid-Level based Operations and Control Strategies

At the grid level, various operational challenges and control methods are essential for managing faults in *VLCs* and enhancing *EV* efficiency. Unexpected power ripples often arise due to unstable 3-ϕ grid voltages and fluctuating loads causing variability in output voltage and current which decreases the efficiency and lifespan of *EV* batteries. Several control methods are employed to address these issues. Active power filters (*APFs*) compensate for dynamic power imbalances in the 3-ϕ system improving 3-ϕ disproportion, reactive power management and addressing harmonics as shown in **Figure 7**.

For handling power quality issues and unbalanced systems, the synchronous detection methods operate effectively in 3-ϕ unbalanced systems by enhancing the efficiency and power factor through phase-wise conversion calculations although they require additional hardware and increases the system costs. Pulse Width Modulation (*PWM*) rectifiers analyze input-output, input power and output power in 2-ϕ steady converters and 3-ϕ boost-type converters under unequal voltage conditions addressing power quality issues using different controllers, filters and series coupling transformers. Space Vector Modulation is implemented with direct power switching using space vector cadence where the controller uses the prompt power concept by deriving power gradients for active and reactive power by effectively cancelling dynamic energy. Network-peak voltage utilizes Clarkes' transformation method to distinguish between explicit and implicit voltages optimizing system regulation and reducing harmonics to improve power quality (*PQ*). Regardless of grid frequency, the virtual synchronous generator generates output power by utilizing *FT* capabilities which operated without proportional- integral (*PI*) controller. By accommodating oscillations in power generation and distribution, it enhances system performance and stability. When the optimal vector range for active and reactive power is reached, the multi-vector analytical power controller method improves the steady-state performance and switching frequency without increasing the system sampling frequency by selecting the active and zero-vectors under non-ideal grid power settings. These approaches mitigate the *PQ* and grid-level fluctuations by enhancing the lifespan and overall performance of EV batteries.

For precisely managing the electricity flow, voltage regulation and frequency control in grid-level operation, it benefits in strengthening the reliability and stability of the power grid. These strategies also address various challenges such as voltage fluctuations and frequency deviations for ensuring smoother grid environment. The other advantages of grid-level operation help in enhancing efficiency which leads to improved load balancing, utilization of renewable energy resources (*RERs*) and better cost saving due to reduced energy losses.

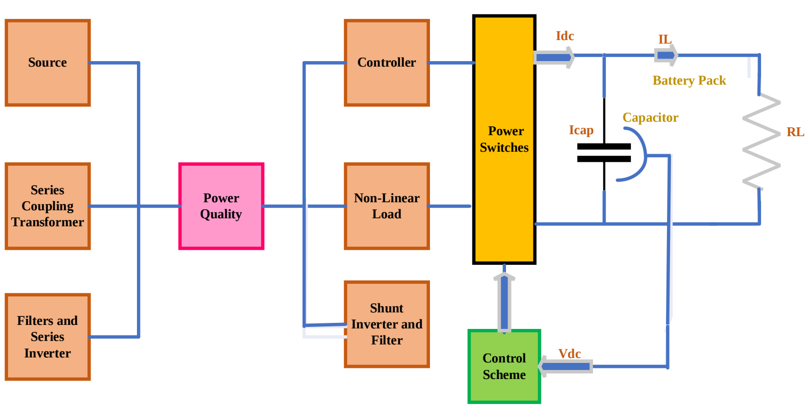

Figure 7. The power quality improvement scheme to reduce harmonics using active power at input (e_{abc}) and DC voltage at output (V_{dc}).

The shortcomings of grid-level operation include the high costs, essential complexity for implementing advanced monitoring of control systems which may need more investments and large upgrades to integrate with existing grid infrastructure. These control strategies depend on communication networks for command transmission and data exchange between grid components which are vulnerable to disruptions, physical damage and cyberattacks. Such vulnerabilities negotiate the overall grid operations and effectiveness of the control strategies.

3.1.2 Module- Level based Operations

In this system, the traditional two-level *AC/DC/AC* converters have been replaced with matrix converters, although reliability remains a significant concern. Several *FT* techniques are employed at this level: output currents are monitored for fault detection without additional devices providing a cost-effective solution; finite set predictive control is utilized to diagnose faults such as single-switch failures; short-circuit currents are easily detected with semiconductors being shut down to prevent damage from short-circuit faults and multi-level converter topologies enhance *DC*-connection voltage and reduce current harmonics which can be evaluated against typical converter types. The integration of a *PI* controller, phase-locked loop (*PLL*), voltage control and a 3-ϕ inverter in the electrical grid facilitates a comparison of phase voltages and reference voltages using sinusoidal pulse-width modulation (*SPWM*) as depicted in **Figure 8**.

Module-level operations offer substantial advantages by providing granular monitoring of individual components such as solar panels within a photovoltaic (*PV*) array. This meticulous oversight enables the early detection of performance issues or faults allowing for prompt maintenance and optimization of overall system efficiency. These operations enhance system performance and energy harvesting for finer control. This operation also offers flexibility to adapt to varying weather conditions and enables modules to operate separately. Thus, this approach results in the addition of power optimizers and microinverters which increases the system cost and complexity. As compared to the traditional centralized methods, module level operation demands high maintenance and high costs. Thus, troubleshooting and monitoring at module level operation are more labor-intensive and time-consuming which requires concentrated equipment for further escalating the maintenance expenditures.

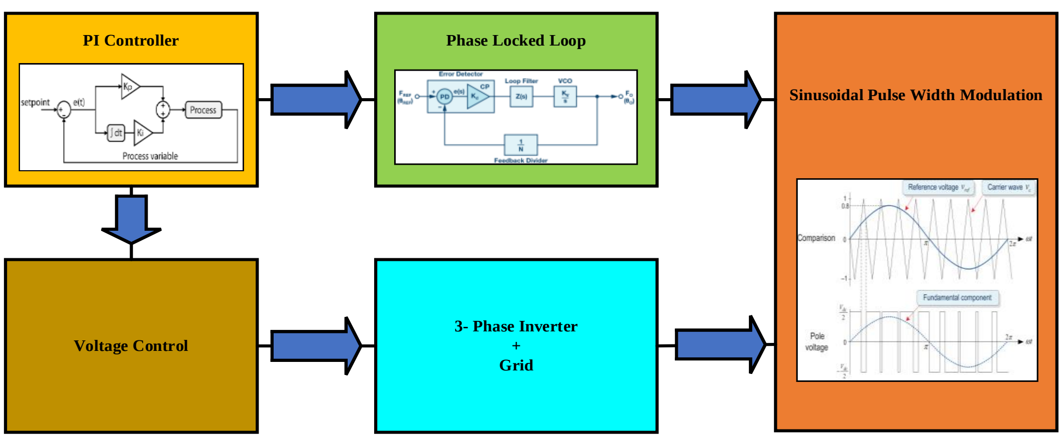

Figure 8. Block diagram demonstrating module level based operation.

3.1.3 Operation in Switch-Level System

In switch-level mode of operation, it concentrates on rectifying and identifying the blips caused due to short-circuits or system failures such that it risks the system veracity. Thus, power semiconductors in this setting suffer from open-circuit (*O.C.*) failures which leads to reduced efficiency and system performance in *VLCs*. The redundancy-based techniques involve duplicating of the critical mechanisms such as switches which provide backup functionality for uninterrupted operation in case of system failure. On fault diagnosis, these strategies facilitate a continuous transition to redundant mechanisms. The adaptive control strategies adjust the operating conditions and control parameters by detecting faults, maintaining operational functions and optimizing system performance under varying environments. These approaches utilize unconventional algorithms to reconfigure the real-time control system. For modifying the *PECs*, *FT* modulation schemes mitigate the effects of faults on system operation as illustrated in **Figure 9.**

FT modulation schemes mitigate the impact of faults on converter performance by adapting switching patterns or duty cycles by ensuring stable and reliable operation. The control strategies for this level of operation include: isolating defective *O.C* switches to address controller malfunctions; utilizing a mid-point-based *DC* bus configuration to enhance cost-efficiency and reduce complexity in fault management; employing parallel and cascaded systems to detect and manage faults during *EV* charging or discharging; balancing unbalanced operating phases during battery charging to protect the system from faults and analyzing voltage vectors and space sectors in three-phase two-level converters to detect faults under adverse conditions.

Following the isolation of faulty sub-modules in switch-level *FT* systems several control strategies are employed to ensure system stability and performance. These include- the redistribution of power where the control system reallocates the load among the remaining functional sub-modules to compensate for the loss of capacity thereby maintaining the stability and load requirements of the *PECs*; the reconfiguration of control parameters which involves adjusting voltage and current settings to accommodate changes in submodule configuration and load distribution, thus ensuring output voltage and current remain within desired limits; fault recognition and monitoring which involves continuously assessing the performance of sub-modules and detecting system abnormalities to prevent further degradation by triggering appropriate responses through fault detection algorithms and adaptive modulation arrangements where modulation schemes adjust switching patterns of the sub-modules to minimize the impact of faults on system efficiency, optimizing performance even with fewer available sub-modules.

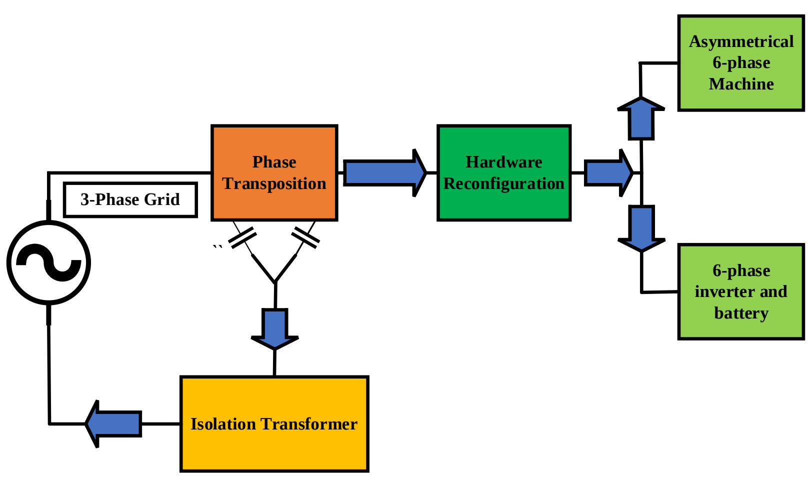

Figure 9. Schematic diagram of switch-level power operation systems.

By enabling the precise control over single switches in an electrical system, the switch-level operation provides substantial benefit by enhancing the power flow management, improved fault isolation which improves the reliability and system performance. This level of operation optimizes the energy distribution, reduced power losses and improved overall system efficiency by allowing switches to activate or deactivate on real-time conditions. It integrates efficiently with *RESs*, *DR* mechanisms and energy storage systems (*ESSs*) by enabling the grid to adapt more competently in varying environmental conditions and Variable demand patterns. This level of operation has certain challenges which risks the system failures and increases its complexity by introducing numerous switches and control strategies. Thus, it necessitates the advanced coordination, monitoring and communication for ensuring reliable operation. Furthermore, the possible equipment malfunctions and human errors at switch level operation compromises the system performance and reliability. The preliminary costs for implementing switch level control consists of actuators, sensors and communication networks. Moreover, for managing and maintaining these systems requires resources and focussed expertise which may pose financial and logistical challenges for operators and utilities.

3.1.4 System-Level Operations

In this level of operation, the autonomous regulation of hybrid multilevel converters coupled with active and reactive power enhances their suitability for high-voltage direct current (*HVDC*) applications. This design requires twofold the number of semiconductor switches as compared to conventional two-level *VSCs*. Modified parallel hybrid converter (*PHC*) integrated with this control strategy provides advanced configurations for managing faults in *VLCs*. The open-switch *FT* control method improves the effectiveness and speed of fault detection algorithms. Fault compensation through batteries and supplementary converters augments system efficiency and reliability as demonstrated in **Figure 10.**

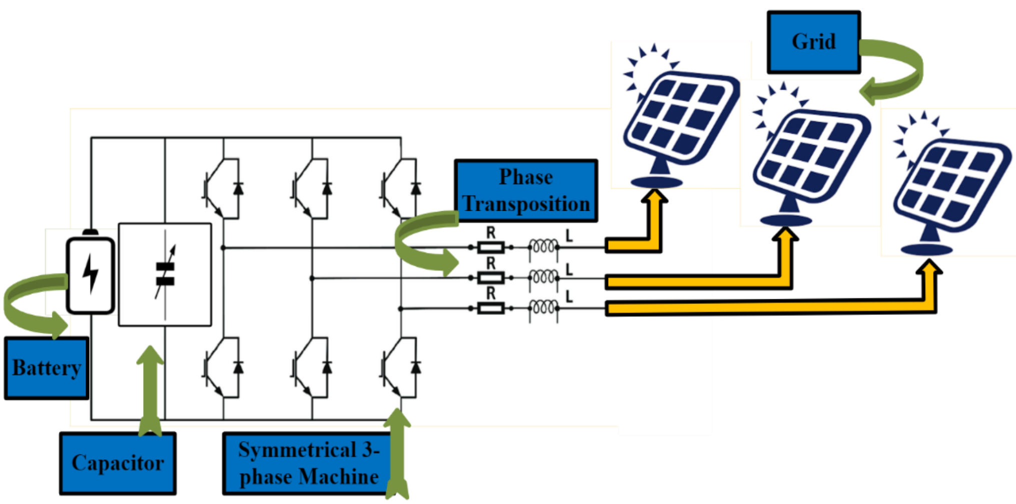

Figure 10. Schematic of system-level operations within a 3-ϕ grid.

The advantages of system-level operations are evident in their capacity to offer comprehensive oversight and coordination across all components within an electrical system. This approach enables optimal resource allocation, efficient load balancing and enhanced grid stability through centralized control and management. It supports the seamless integration of various generation sources, energy storage systems (*ESSs*) and demand-side management resources (*DSM*) by improving asset utilization and overall system performance. However, system-level operations are susceptible to single points of failure or bottlenecks which can adversely affect the entire system. A malfunction or disruption in the central control infrastructure could precipitate widespread outages or a marked decline in system performance. Also, the reliance on centralized control may constrain the system scalability and flexibility especially in dynamic or decentralized environments. For maintaining the system-level control infrastructure, the cost and complexity poses a significant challenge for the adoption and deployment of less-developed grid systems.

3.1.5 Measurement-Level Operations

In measurement-level of operation, *VLCs* evaluate the factors like environmental disturbances, human errors, device ageing and mechanical vibration. These factors affect the operation of electrical machines and impact the performance of the system. For improving overall system efficiency, the feedback control system is the fundamental mode of operation which detects the deviations and controls it. Single-phase to three-phase *VLCs*-coupled filtering scheme (*CFS*) integrated with this control method and *FT* supervisory control within hybrid *AC/DC* microgrids leverages sensors for detecting faults and real-time battery parameter estimation. It continuously analyzes and monitors system parameters such as voltage and current through sensor data set. This real-time statistic provides important insights to system performance through *PECs* precise control and regulation as illustrated in **Figure 11**. To maintain optimal system functionality, the detected faults and deviations cause immediate corrective actions. Therefore, this operation mode enhances the reliability, safety and efficiency of power electronic devices.

The major benefits for this mode of operation provides a precise real-time monitoring and data acquisition capabilities. Within electrical networks, the operators gain the valuable insights into system performance, behaviour and condition by capturing the voltage, current and power data from individual components or nodes. This capability enhances the system reliability, efficiency and maintenance schedules by enabling pre-emptive issue detection and targeted troubleshooting with initial anomaly detection. For optimizing system operations, accurate measurement data supports better decision making by improving system resilience and performance. Thus, it increases the data processing demands and complexity of the system.

Numerous measurement points require a vigorous communication infrastructure, substantial computational sources and effective data management systems for managing the data. For handling the real-time measurement data in large-scale or high-density electrical circuits poses various challenges related to latency, storage capacity and bandwidth. The system necessitates synchronization, quality control measurements and calibration for ensuring data consistency, reliability and accuracy which add to the system cost and operational expenses.

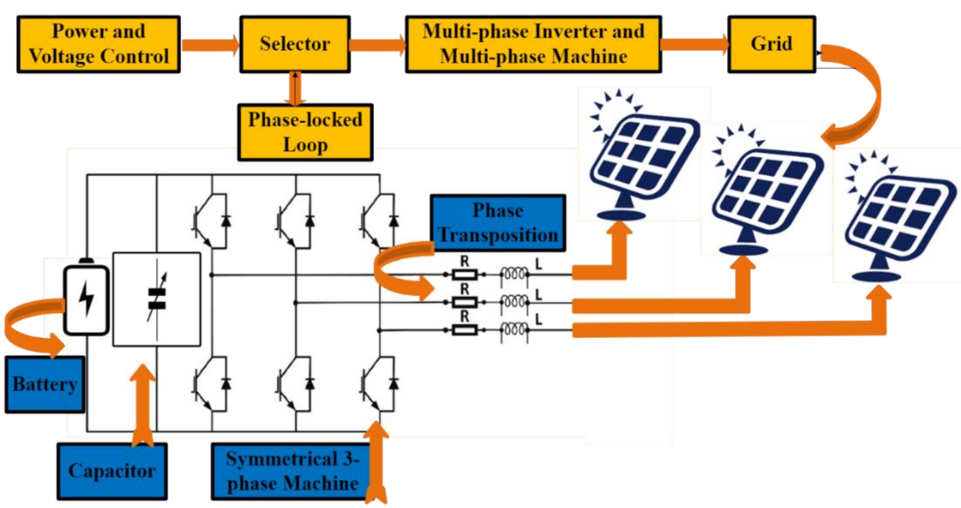

Figure 11. Representation of a multiphase machine in measurement-level operation.

4. Results and Discussion

In this section, a comparison of multiple control methods like *APF*, *PI* control, Multi-Vector Model Predictive Power (*MV-MPPC*), Model Predictive Control (*MPC*), power controllers, input controllers and current compensation with various modes of operation in *VLCs*. The critical parameters have the following evaluation criteria which includes power density, control complexity, input and output voltage, hardware configuration and isolation. A comprehensive landscape of *VLCs* offers comparison of operational modes. For each operational mode such as module level, grid level, system level, switch level and measurement level comprehensive input data has been utilized which has been presented in **Tables 3** to **7**.

A comprehensive analysis of the data points for different level of operation requires each control method for addressing critical aspects such as efficiency, topology, power density, voltage regulation and control complexity. For maintaining the grid stability and efficient power conversion through precise voltage regulation, *PI* control ensures consistent performance during faulty conditions. During faults, *APF* is designed to reduce *THD* and enhances the *PQ* by filtering out redundant frequencies and improving grid resilience. By adjusting the current levels to alleviate the grid conditions, current compensation methods prioritize fault isolation and detection which prevents cascading failures. For different grid environments, input power controllers focus on voltage stability and optimizing power conversion efficiency supports fault resilience and robust operation. Thus, to manage and anticipate the fault conditions *MPC* employs advanced predictive algorithms for ensuring reliable operation with marginal system disruption.

Table 3 provides evaluation of different control methods in grid-level mode of operation which enhances the power characteristics of the system without any need of additional hardware configurations. The table highlights optimum values designed for simplifying the *VLCs* complexity using different control methods to address *PQ* issues. Thus, a review of significant literature (Kim et al., 2020; Pradeep et al., 2023) evaluates power density and diverse topologies by emphasizing their pertinency towards *VLCs* that have been integrated *FT* techniques at leg, switch or module levels. These references maintain compatibility with *VLC* controllers and offer practical implementation with various control methods without requiring any additional hardware configurations. Single or dual-phase *PECs* withing smart grids (*SGs*) and microgrids (μGs) are commonly employed with *FT* based grid-level techniques which acts as a fundamental part of their subsystems.

Figure 12 depicts the harmonic spectrum of an asymmetrical 6-winding configuration operating in grid-level mode and showcases the different frequencies of voltage spectrum. The harmonic magnitudes are determined by extracting amplitudes via Fourier analysis and normalizing these amplitudes against frequency. Under ideal conditions, the voltage spectrum should prominently display the fundamental frequency component, indicative of the sinusoidal waveform characteristic of a well-functioning electrical grid albeit with varying magnitude values. This voltage spectrum analysis is crucial for assessing the quality of electrical power delivered to the grid. Elevated harmonic content can lead to several issues including increased losses in electrical equipment, disruptions in communication systems and a degradation in *PQ*. Therefore, meticulous monitoring and regulation of the voltage spectrum are essential for maintaining grid stability and ensuring reliable, consistent power delivery to consumers.

Table 4 provides a comparative analysis of various module-level modes of operation for *VLCs*. In this mode, *VLCs* are capable of swiftly detecting and isolating faults from the grid offering an effective technique for managing current faults. This approach is versatile applicable to 1-ϕ, dual-ϕ and 3-ϕ systems. Among the control methods employed in a 3-ϕ module-level system are *PI* control, voltage control, phase control and voltage-oriented control. The highest system efficiency is attained with the *PI* controller operating at an input voltage of 210 V_{dc} and an output voltage of 110 V_{ac}.

Table 3. Evaluation of control methods in grid level mode of operation.

Grid-Level mode of operation							
References	**Control method**	**Input voltage**	**Output voltage**	**Efficiency**	**Topology**	**Control complexity**	**Power density**
Gaona-Cárdenas et al. (2022)	PI	142 V_{ac} (3-φ)	420 V_{dc}	85.4%	PWM AC/DC	High	100
	Active power filter	380 V_{ac} (3-φ)	740 V_{dc}	80–90%	3- φ, AC/DC	Medium	140
	Current compensation	110-80 V_{ac} (3-φ)	--	90-95%	3- φ, AC/DC	Medium	100
	Input power controller, input-output power control, and output power controller	170 V_{ac} (3-φ)	310 V_{dc}	75-85%	3- φ, AC/DC	Medium	100
Kim et al. (2020)	Explicit power controller	160 V_{ac} (3-φ)	310 V_{dc}	80%	2-Level PWM Rectifier	Medium	100
	MV-MPPC	110 V_{ac} (3-φ)	300 V_{dc}	85%	3- φ Rectifiers	High	130
	Voltage/current controller	70 V_{ac} (3-φ)	250 V_{dc}	80%	PWM Rectifiers	Medium	100
Jin et al. (2017)	Model predictive controller (MPC)	110 V_{ac} (3-φ)	420 V_{dc}	85-90%	3- φ, AC/DC	High	160
	Current Controller	120 V_{ac} (3-φ)	280 V_{ac} (3-φ)	85-90%	3- φ, Inverter	High	150

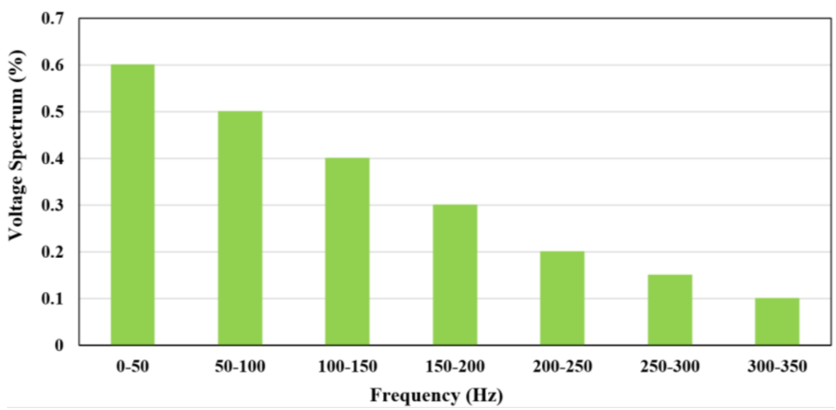

Figure 12. Harmonic spectra of asymmetrical six-phase winding configuration.

Table 4. Comparison based on module level mode of operation.

Module-Level mode of operation							
References	**Control method**	**Input voltage**	**Output voltage**	**Efficiency**	**Topology**	**Control complexity**	**Power density**
Zhang et al. (2024)	PI	210 V_{dc}	110 V_{ac} (3-φ)	85–95%	3-level inverter	Medium	67
	Voltage Control	210 V_{dc}	80 V_{ac} (3-φ)	90%	Multilevel converter	Medium	20
	Phase control	50 V_{ac} (3-φ)	150 V_{dc}	85%	3-Level Rectifier	Medium	100
	Voltage/Current Control	310 V_{ac} (3-φ)	110 V_{ac} (3-φ)	90%	Matrix	High	125
Musavi et al. (2011)	Voltage Oriented Controller	230 V_{ac} (3-φ)	120 V_{ac} (3-φ)	82–85%	Matrix	Medium	60
		310 V_{ac} (3-φ)	210 V_{dc}	80–90%	Twelve-Pole Inverter	High	70

The implementation of redundancy-based architectures is significantly bolstered by adaptive control algorithms and *FT* modulation schemes which enhance the reliability and performance of module-level converters. By integrating isolation and bypass mechanisms coupled with predictive maintenance strategies, these approaches ensure continuous operation and minimize downtime. Such management options not only improve *FT* but also optimize system performance and extend the equipment's operational lifespan by enhancing the overall reliability and efficiency of power systems. The voltage spectrum versus frequency calculated at a maximum efficiency of 95% is illustrated in **Figure 13**.

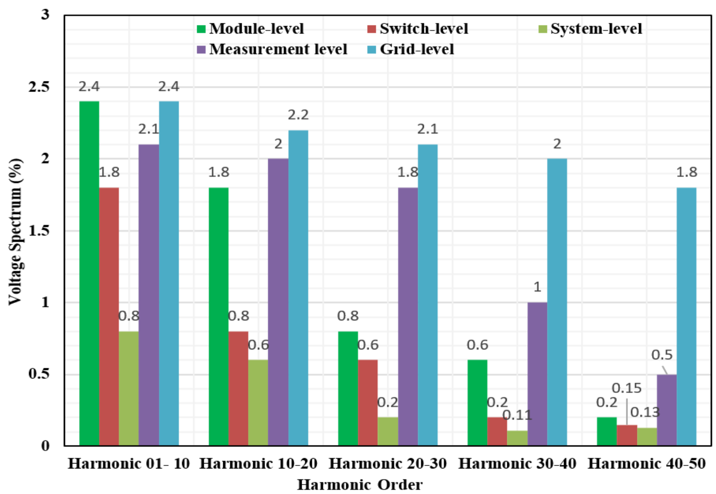

Figure 13. Harmonic spectra analysis for different levels of operation.

The harmonic spectra for module level, switch level, system level, measurement level and grid level operations within 6-ϕ winding configurations have been detailed. The harmonic order ranging from 0 to 50 represents the percentage (%) of the voltage spectrum across all operational levels. The maximum voltage spectrum analysis shows that for harmonic orders 1 to 10, the voltage spectrum percentage is 2.4 for both grid-level and module-level modes. For harmonic orders 10 to 20, the voltage spectrum is 2.2 at the grid level. For harmonic orders 20 to 30, the voltage spectrum percentage is 2.1 at the grid level. At harmonic orders 30 to 40, the voltage spectrum is 2.0 at the grid level and for harmonic orders 40 to 50, it is 1.8 at the grid level.

Table 5 illustrates the switch-level fault-tolerance techniques which incorporate various control methods to enhance hardware quality in a 3-ϕ system. A key challenge in switch-level operation is ensuring fault acceptance for reconfigurable 1-ϕ, dual-ϕ isolated and 3-ϕ supplies. The use of controllers such as fuzzy logic and lead-lag compensators significantly improves system efficiency and switching capabilities addressing these challenges effectively.

Figure 14 illustrates the variations in charging currents, voltages and total harmonic distortion (*THD*) in *VLCs* relative to voltage percentage (%). During one half-cycle, the current increases by 20%, accompanied by a reduction in *THD* by 40%. Conversely, in the subsequent half-cycle, the current decreases by 60%, while *THD* rises by 70%. This indicates that elevated *THD* levels correlate with a decline in *PQ* of the system. Thus, in the first half-cycle where *THD* is lower, the system exhibits higher reliability and maintains optimal *PQ*.

Table 5. Comparison based on switch level mode of operation.

Switch-level mode of operation							
References	**Control method**	**Input voltage**	**Output voltage**	**Efficiency**	**Topology**	**Control complexity**	**Power density**
Manjrekar et al. (2000)	Current Control	230 V_{ac} (3-φ)	420 V_{dc}	75–85%	3-φ, AC/DC	High	150
		60 V_{ac} (3-φ)	--	86%	3-φ, AC/DC	Medium	50
	Voltage Control	230 V_{ac} (3-φ)	420 V_{dc}	80–90%	3-φ, AC/DC	High	180
	Neutral Point Control	110 V_{dc}	220–250 V_{ac} (3-φ)	90%	T-Type 3-Level Inverter	High	60
Abraham et al. (2021)	Voltage oriented control	60 V_{ac} (3-φ)	320 V_{dc}	90%	Back-to-Back	High	30
	Predictive Control	60 V_{ac} (3-φ)	220 V_{dc}	85%	3-φ, AC/DC	High	50
	Fuzzy	14 kV_{ac} (3-φ)	22 kV_{dc}	85–95%	3-φ, AC/DC	Low	250
	Lead-lag compensator	12 V_{dc}	10 V_{dc}	85–95%	Buck	Low	60

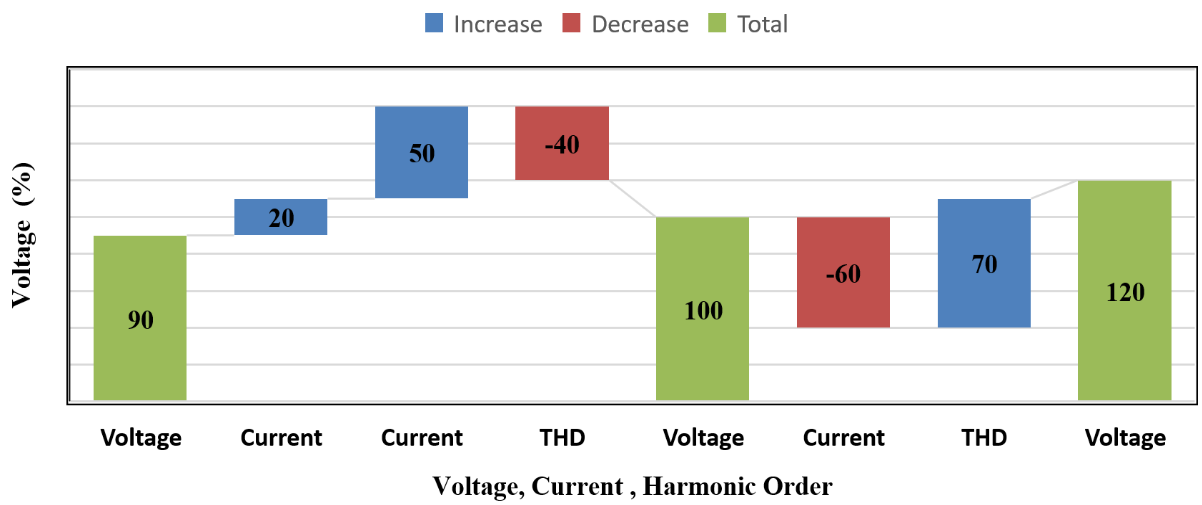

Figure 14. Variation of charging currents, charging voltages and total harmonic distortion in VLCs.

Table 6 provides a comparative analysis of the system-level mode of operation which oversees the coordination and management of various components within a comprehensive electrical or electronic framework. This operational tier encompasses tasks such as system initialization, synchronization, fault detection, fault handling and overall system control to ensure effective integration and performance of subsystems. It often involves the application of sophisticated algorithms and communication protocols that facilitate seamless interaction among subsystems by significantly enhancing system efficiency, reliability and safety. The current control method, employing a 3-ϕ *AC/DC* converter achieves optimal efficiency of 86% at 80 V_{ac} underscoring its efficacy in system-level operations.

Table 6. Comparison based on system level mode of operation.

System-Level mode of operation							
References	**Control method**	**Input voltage**	**Output voltage**	**Efficiency**	**Topology**	**Control complexity**	**Power density**
Abraham et al. (2021)	DC Voltage Compensation	220 kV_{ac} (3-φ)	310 kV_{dc}	85%	Twin Hybrid Multilevel	High	600
Abdel-Khalik et al. (2016)	PI	130 kV_{ac} (3-φ)	210 kV_{dc}	80%	Twin Hybrid Multilevel	Medium	600
		50 V_{ac} (3-φ)	190 V_{dc}	85%	Twin Hybrid Modular Multilevel	Low	80
	Current Control	80 V_{ac} (3-φ)	130 V_{dc}	80%	3-φ, 2-Parallel AC/DC	High	250
	State Vector Machine (SVM)	35 kV_{ac} (3-φ)	1200 V_{dc}	86%	2-Parallel AC/DC	Medium	700

Figure 15 illustrates the temporal variation of the grid phase voltage for a single-system machine which shows a decrease over time. The grid phase voltage peak reaches at 180 V with the lowest phase voltage dropping to 80 V. Thus, maintaining the temporal stability in grid phase voltage is crucial for ensuring reliable and consistent electrical power distribution. The variations in phase voltages can significantly affect the performance of electrical apparatus and the quality of power delivered to customers. Continuous monitoring facilitates early anomaly detection allowing for prompt corrective actions to prevent potential disturbances. The stable grid phase voltage supports enhanced power management approaches and overall grid stability indicating optimal performance at 180 V within 0.8 seconds.

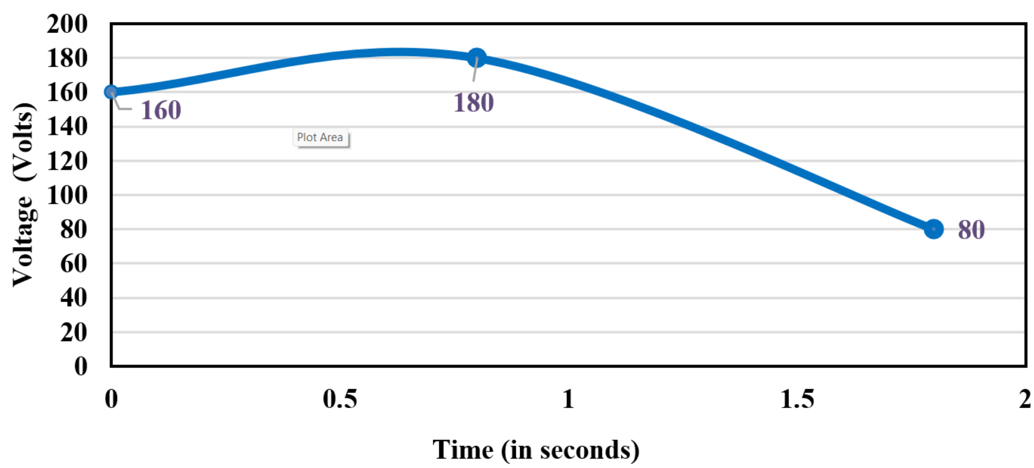

Figure 15. Grid phase voltage.

Table 7 provides a comparative analysis of the measurement-level mode of operation utilizing various control techniques. These techniques are not highly adaptable which allow seamless integration with other methods and distinguished by their ease of implementation and reduced complexity. Furthermore, the application of deep learning (*DL*) models can significantly enhance system performance by minimizing errors by increasing the overall efficacy of these measurement techniques.

Table 7. Comparison of control methods in measurement level mode of operation.

Measurement-level mode of operation							
References	**Control method**	**Input voltage**	**Output voltage**	**Efficiency**	**Topology**	**Control complexity**	**Power density**
Singh et al. (2003)	PI	210 V_{ac} (3-φ)	410 V_{dc}	85%	3-φ AC/DC	Low	100
		230 V_{ac} (3-φ)	370 V_{dc}	90%	3-φ AC/DC/AC	Low	110
	Transient current control	1555 V_{ac} (1-φ)	2800-3700 V_{dc}	82%	PWM Rectifier	Low	300
	Sliding mode controller (SMC)	610 V_{ac} (3-φ)	390 V_{dc}	88%	Hybrid AC/DC	Low	150
	Adaptive control	100 V_{dc}	230 V_{dc}	87%	PWM Inverter	Low	140

Figure 16 depicts the variations in voltage, time and temperature configurations of VLCs within the measurement-level mode of operation over different time periods. The temperature range extending from -100°C to 100°C plays a key role in enhancing VLC performance by improving battery efficiency and reducing heat losses.

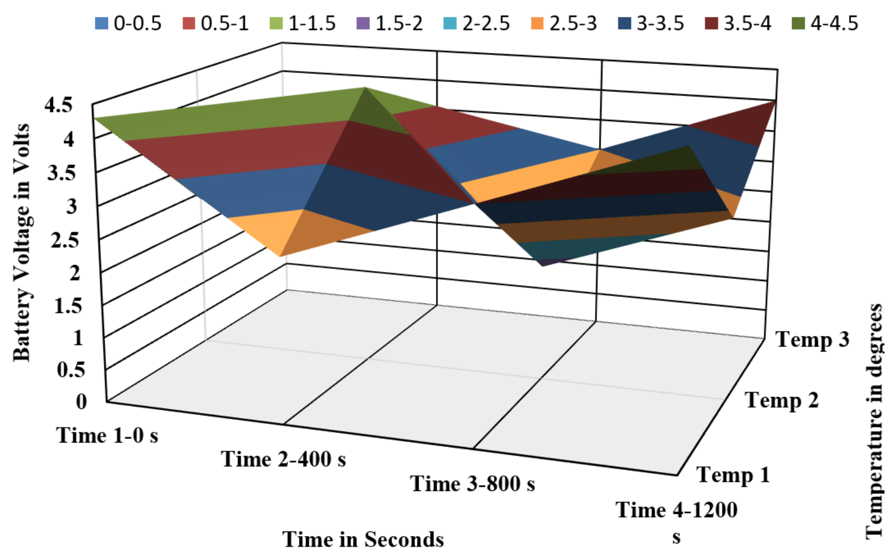

Figure 16. Voltage, temperature and time configurations of VLCs.

Therefore, the relationship between battery voltage, temperature and time is vital for assessing battery health and performance. The voltage variations over time provide valuable indicators of battery degradation and the dynamics of charging and discharging cycles. Temperature fluctuations significantly influence battery voltage, overall efficiency and capacity. Continuous monitoring of battery voltage with consideration of both thermal and temporal factors enables pre-emptive maintenance and optimization of battery utilization. Interdependencies is essential for ensuring a reliable energy storage solution and prolonging battery lifespan.

Figures 12 to **Figure 16** illustrate the analysis of voltages in relation to current, temperature, time and *THD* highlighting the hardware configurations with various control strategies and *FT* techniques. These approaches are extensively employed to address *PQ* issues, enhance grid stability and design more reliable systems. The emphasis is on improving the reliability and compatibility of *VLCs* through the integration of *FT* techniques and diverse control methods.

5. Conclusion and Future Work

This paper provides an in-depth assessment of the current landscape of *EV* battery chargers focusing on charging power levels and associated infrastructure. It addresses critical parameters such as battery performance, types, designs and the characteristics of charging equipment and infrastructure. The study classifies battery charging into three levels- Level 1, Level 2 and Level 3 charging and distinguishes between two primary charger systems: off-board and on-board. It explores the distinctions between unidirectional and bidirectional power flows. Unidirectional charging simplifies hardware requirements, reduces interconnection complexities and can help alleviate battery depletion whereas bidirectional charging allows excess battery energy to be fed back into the grid. *OBCs* constrained by weight, space and cost offer an alternative avenue for integrating power-driven systems facilitating cost-effective, high-power, bidirectional fast charging with a unity power factor using Level 2 and Level 3 chargers.

Furthermore, well-established charging infrastructure can minimize the need for extensive on-board energy storage resulting in cost savings. The paper also differentiates between conductive and inductive on-board charging techniques with the latter undergoing active research. A comparative analysis of various *VLCs* power quantities and configurations is presented considering factors such as power capacity, charging duration, location, cost and equipment requirements. Additionally, the paper examines control strategies based on voltage, current and temperature for *EV* chargers demonstrating their effectiveness by significantly reducing *THD* from 60% to 40%, 40% to 20% and 20% to -40%. The results affirm the efficacy of single-tuning filters using fuzzy, lead-lag and *PI* controllers in mitigating *THD* and enhancing system reliability and compatibility. Among all operational modes, grid-level operation, utilizing *PI* controllers emerges as the most effective for grid stability with minimal harmonic distortion. The study acknowledges its focus on specific *FT* techniques while highlighting the need for further exploration of other methods. While *PQ* in *PECs* is not the primary focus, only improvements in *THD* are addressed.

Future research should explore the scalability, cost and long-term performance of these strategies under diverse conditions. Emerging trends include advancements in machine design, controller technology and converter topologies pollutants reflecting ongoing efforts to address challenges and opportunities in *PQ* improvement and system loss minimization.

Abbreviations

VLC	Vehicular loaded Charger
CFS	Coupled filtering scheme
HEV	Hybrid electric vehicle
PHEV	Plug-in hybrid electric vehicle
MOSFET	Metal oxide semiconductor field effect transistor
EV	Electric vehicle
FT	Fault tolerance
APF	Active power filter
BJT	Bipolar Junction transistor
AC	Alternating Current
DC	Direct current
PQ	Power quality
PI	Proportional Integral
SVM	State vector Machine
PHC	Parallel hybrid converter
PLL	Phase locked loop
PWM	Phase width modulation

PHMC	Parallel hybrid multilevel converter
SPWM	Sinusoidal pulse width modulation
MPC	Model predictive control
MMC	Modular multilevel converters
SCR	Silicon controlled rectifier
IM	Induction motors
PMSM	Permanent magnet synchronous motors
SRM	Switched reluctance motor
CMC	Cascaded multilevel converters
EVSE	Electrical vehicle supply equipment
BEV	Battery electric vehicles
FSCW	Fractional slot concentrated winding
SMC	Sliding mode controller
PECs	Power electronic converters
CS	Charging station
MV-MPPC	Multi vector model predictive power control
DR	Demand response
ML	Machine learning
RER	Renewable energy resources
RES	Renewable energy sources
DL	Deep learning
EVSE	Electric vehicle supply equipment

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

The authors extend their appreciation to the Researchers Supporting Project at King Saud University, Riyadh, Saudi Arabia, for funding this research work through the project number RSP2023R278.

The authors extend their appreciation to the Researchers Supporting Project at Universiti Teknologi Malaysia (UTM), Malaysia (project no. UTMFR: Q.J130000.3823.23H05).

The authors extend their appreciation to Intelligent Prognostic Private Limited Delhi, India; Department of Electrical Engineering, Jamia Millia Islamia, New Delhi, India; Department of Energy Sciences and Engineering, Indian Institute of Technology Delhi, India; and Universiti Sultan Zainal Abidin (UniSZA) Malaysia for providing technical and non-technical support in this research work.

For the correspondence, please contact the corresponding author(s) at MajedAlotaibi@ksu.edu.sa (Majed A. Alotaibi), hasmat@utm.my (Hasmat Malik), asyrafafthanorhan@unisza.edu.my (Asyraf Afthanorhan), md.amir@ieee.org (Mohammad Amir).

References

Abdel-Khalik, A.S., Ahmed, S., & Massoud, A.M. (2016). A six-phase 24-slot/10-pole permanent-magnet machine with low space harmonics for electric vehicle applications. *IEEE Transactions on Magnetics, 52*(6), 1-10. http://dx.doi.org/10.1109/tmag.2016.2535230.

Abraham, D.S., Verma, R., Kanagaraj, L., Raman, S.R.G.T., Rajamanickam, N., Chokkalingam, B., Marimuthu Sekar, K., & Mihet-Popa, L. (2021). Electric vehicles charging stations' architectures, criteria, power converters, and control strategies in microgrids. *Electronics, 10*(16), 1895. https://doi.org/10.3390/electronics10161895.

Ali, I., & Sharma, S. (2022). Design and implementation of energy efficiency augmentation using renewable energy source for small-scaled residential micro-grid. In: Bansal, R.C., Agarwal, A, Jadoun, V.K. (eds) *Advances in Energy Technology*. Springer, Singapore. pp. 693-702. https://doi.org/10.1007/978-981-16-1476-7_62.

Amir, M., Zaheerudddin., & Haque, A. (2021). Integration of EVs aggregator with microgrid and impact of V2G power on peak regulation. In *2021 IEEE International Conference on Computing, Power and Communication Technologies* (pp. 1-6). IEEE. Kuala Lumpur, Malaysia. https://doi.org/10.1109/gucon50781.2021.9573619.

Amir, M., Zaheeruddin, A.H., Bakhsh, F.I., Kurukuru, V.S.B., & Sedighizadeh, M. (2024). Intelligent energy management scheme-based coordinated control for reducing peak load in grid-connected photovoltaic-powered electric vehicle charging stations. *IET Generation, Transmission & Distribution*, *18*(6), 1205-1222. https://doi.org/10.1049/gtd2.12772.

Bai, Y., Yang, X., Zhang, D., Li, X., Chen, W., & Hu, W. (2017). Conducted EMI mitigation schemes in isolated switching-mode power supply without the need of a Y-capacitor. *IEEE Transactions on Power Electronics*, *32*(4), 2687-2703. https://doi.org/10.1109/tpel.2016.2579679.

Bukya, M., Sharma, S., Kumar, R., Mathur, A., Gawtham, N., & Kumar P. (2024). Electric vehicle grid demand: Potential analysis model and regional architectural planning approach for charging using PVsyst tool. *Visions for Sustainability*, *2024*(21), 209-232. https://doi.org/10.13135/2384-8677/8869.

Gaona-Cárdenas, L.F., Vázquez-Nava, N., Ruíz-Martínez, O.F., Espinosa-Calderón, A., Barranco-Gutiérrez, A.I., & Rodríguez-Licea, M.A. (2022). Survey on an overview on fault management for electric vehicle onboard chargers. *Electronics*, *11*(7), 1107. https://doi.org/10.3390/electronics11071107.

Herrera, D., Villegas, J., Galván, E., & Carrasco, J.M. (2019). Synchronous reluctance six-phase motor proved based EV powertrain as charger/discharger with redundant topology and ORS control. *IET Electrical Power Applications*, *13*(11), 1857-1870. https://doi.org/10.1049/iet-epa.2018.5338.

Jin, N., Guo, L., & Yao, G. (2017). Model predictive direct power control for nonredundant fault tolerant grid-connected bidirectional voltage source converter. *Energies*, *10*(8), 1133. https://doi.org/10.3390/en10081133.

Karimi, S., Gaillard, A., Poure, P., & Saadate, S. (2008). FPGA-based real-time power converter failure diagnosis for wind energy conversion systems. *IEEE Transactions on Industrial Electronics*, *55*(12), 4299-4308. https://doi.org/10.1109/tie.2008.2005244.

Ke, S., Yang, J., Chen, L., Fan, P., Shi, X., Li, G., & Wu, F. (2024). A frequency control strategy for EV stations based on MPC-VSG in islanded microgrids. *IEEE Transactions on Industrial Informatics*, *20*(2), 1819-1831. https://doi.org/10.1109/tii.2023.3281658.

Kim, S.H., Kim, S.M., Park, S., & Lee, K.B. (2020). Switch open-fault detection for a three-phase hybrid active neutral-point-clamped rectifier. *Electronics*, *9*(9), 1437. https://doi.org/10.3390/electronics9091437.

Lee, S.J., & Sul, S.K. (1994) An integral battery charger for 4 wheel drive electric vehicle. *Proceedings of 1994 IEEE Industry Applications Society Annual Meeting* (Vol. 1, pp. 448-452). IEEE. Denver, CO, USA. https://doi.org/10.1109/IAS.1994.345445.

Malik, J.A., Haque, A., & Amir, M. (2023). Investigation of intelligent deep convolution neural network for DC-DC converters faults detection in electric vehicles applications. *International Conference on Recent Advances in Electrical, Electronics & Digital Healthcare Technologies* (pp. 139-144). IEEE. New Delhi, India. https://doi.org/10.1109/reedcon57544.2023.10150998.

Manjrekar, M.D., Steimer, P.K., & Lipo, T.A. (2000). Hybrid multilevel power conversion system: a competitive solution for high-power applications. *IEEE Transactions on Industry Applications*, *36*(3), 834-841. https://doi.org/10.1109/28.845059.

Musavi, F., Eberle, W., & Dunford, W.G. (2011). A high-performance single-phase bridgeless interleaved PFC converter for plug-in hybrid electric vehicle battery chargers. *IEEE Transactions of Industrial Applications*, *47*(4), 1833-1843. http://dx.doi.org/10.1109/tia.2011.2156753.

Park, J.H., Lee, J.S., Kim, M.Y., & Lee, K.B. (2021). Diagnosis and tolerant control methods for an open-switch fault in a Vienna rectifier. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, *9*(6), 7112-7125. http://doi.org/10.1109/jestpe.2021.3084803.

Pradeep, D.J., Kumar, Y.V.P., Siddharth, B.R., Reddy, C.P., Amir, M., & Khalid, H.M. (2023). Critical performance analysis of four-wheel drive hybrid electric vehicles subjected to dynamic operating conditions. *World Electric Vehicle Journal*, *14*(6), 138. https://doi.org/10.3390/wevj14060138.

Salkuti, S.R. (2023). Advanced technologies for energy storage and electric vehicles. *Energies*, *16*(5), 2312. https://doi.org/10.3390/en16052312.

Sharma, S., & Ali, I. (2023). Optimized electric vehicle charging and discharging with sporadic renewable energy source. *International Conference on Power, Instrumentation, Energy and Control* (pp. 1-6). IEEE. Aligarh, India. https://doi.org/10.1109/piecon56912.2023.10085780.

Sharma, S., & Ali, I. (2024). Dynamic pricing strategy for efficient electric vehicle charging and discharging in microgrids using multi-objective Jaya algorithm. *Engineering Research Express*, *6*(3), 035315. http://dx.doi.org/10.1088/2631-8695/ad6394.

Sharma, S., Ali, I., & Aftab, M.A. (2022). Demand response mechanism in user-centric markets integrated with electric vehicles. *IEEE Delhi Section Conference* (pp. 1-6). IEEE. New Delhi, India. https://doi.org/10.1109/delcon54057.2022.9753579.

Singh, B., Singh, B.N., Chandra, A., Al-Haddad, K., Pandey, A., & Kothari, D.P. (2003). A review of single-phase improved power quality AC-DC converters. *IEEE Transactions on Industrial Electronics*, *50*(5), 962-981. https://doi.org/10.1109/tie.2003.817609.

Subotic, I., Bodo, N., & Levi, E. (2016b). An EV drivetrain with integrated fast charging capability. IEEE *Transactions on Power Electronics*, *31*(2), 1461-1471. http://dx.doi.org/10.1109/tpel.2015.2424592.

Subotic, I., Bodo, N., Levi, E., Dumnic, B., Milicevic, D., & Katic, V. (2016a). Overview of fast on-board integrated battery chargers for electric vehicles based on multiphase machines and power electronics. *IET Electric Power Applications*, *10*(3), 217-229. https://doi.org/10.1049/iet-epa.2015.0292.

Thimmesch, D. (1985). An SCR inverter with an integral battery charger for electric vehicles. *IEEE Transactions on Industry Applications*, *IA-21*(4), 1023-1029. https://doi.org/10.1109/tia.1985.349573.

Zakaria, A., Marei, M.I., & Sattar, A.A. (2016). A Fault-tolerant strategy for current controlled PWM rectifier. In *Eighteenth International Middle East Power Systems Conference* (pp. 461-467). IEEE. Cairo, Egypt. http://dx.doi.org/10.1109/mepcon.2016.7836931.

Zhang, B., Tang, W., Liang, J., Zhang, L., & Zhao, C. (2024). EV integration-oriented DC conversion of AC low-voltage distribution networks and the associated adaptive control strategy. *IEEE Transactions on Transportation Electrification*, *10*(1), 213-223. http://dx.doi.org/10.1109/tte.2023.3254372.

Zhou, D., & Tang, Y. (2019). A model predictive control-based open-circuit fault diagnosis and tolerant scheme of three-phase AC-DC rectifiers. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, *7*(4), 2158-2169. http://dx.doi.org/10.1109/jestpe.2018.2888879.

Zuo, Y., Zhu, X., Si, X., & Lee, C.H.T. (2021). Fault-tolerant control for multiple open-leg faults in open-end winding permanent magnet synchronous motor system based on winding reconnection. *IEEE Transactions Power Electronics*, *36*(5), 6068-6078. http://dx.doi.org/10.1109/tpel.2020.3030237.

Publisher's Note- Ram Arti Publishers remains neutral regarding jurisdictional claims in published maps and institutional affiliations.