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Study on Grid Stability of Electric Vehicle Bidirectional Charging Device Based on Bidirectional Power Electronic Converter

Jiarong Lin

School of Engineering, University of Edinburgh, United Kingdom

Corresponding author: s2603325@ed.ac.uk

Abstract:

With the increasing number of electric vehicles (EVs), V2G (Vehicle-to-Grid) and G2V (Grid-to-Vehicle) technologies have garnered growing attention as essential methods for energy flow between EVs and the power grid. This study examines the impact of EV charging devices, based on bidirectional power electronic converters, on grid stability. As EVs become more widely adopted, V2G and G2V technologies are extensively applied to enable bidirectional energy flow between EVs and the grid. This study analyzes different topologies of power electronic converters and explores how optimized control strategies can enhance grid voltage and frequency stability. The research shows that bidirectional charging devices provide significant advantages in addressing voltage fluctuations and frequency instability, especially in peak shaving and valley filling, effectively easing grid load. Furthermore, future developments in bidirectional charging devices will focus on intelligent control and synergistic optimization with renewable energy to improve grid stability and power quality. The research methods include analysis and comparison of different converter topologies. Results indicate that bidirectional charging devices have a significant effect in resolving grid instability issues, supporting the further advancement of smart grids).

Keywords: Bidirectional charging device; V2G; G2V; power electronic converter; grid stability.

1. Introduction

As global demand for reducing carbon emissions and achieving sustainable transportation grows, the adoption of electric vehicles (EVs) has been rapidly increasing. V2G (Vehicle-to-Grid) and G2V (Grid-to-Vehicle) technologies have become essential methods for enabling bidirectional energy flow between EVs and the power grid. According to Evaluating the Vehicle-to-grid Potentials by Electric Vehicles: A Quantitative Study in China by 2030 by Zhenya Ji [1], these technologies can optimize EV

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charging and also allow EV batteries to feed power back to the grid, helping to balance grid load and improve grid stability and sustainability. However, the large-scale integration of EVs into the grid also introduces issues such as voltage instability and harmonic distortion, requiring more efficient bidirectional power electronic converters to address these challenges.

This study aims to explore the role of bidirectional charging devices in enhancing grid stability, particularly by optimizing topology and control strategies to improve voltage and frequency stability. By analyzing the operating principles of bidirectional power electronic converters and their application in EV-grid interactions, this research not only provides technical support for smart grid development but also offers critical insights for addressing the stability issues caused by large-scale EV integration into the grid.

2. Application of Bidirectional Charging Devices in Electric Vehicle Charging Systems

2.1 Concept and Advantages of Bidirectional Charging Devices for Electric Vehicles

The bidirectional charging device is a core component of the V2G (Vehicle-to-Grid) and G2V (Grid-to-Vehicle) systems, with bidirectional power electronic equipment at its heart. This equipment enables the EV's battery to function as a distributed energy storage unit, allowing energy to flow bidirectionally between the power grid and the electric vehicle. It can charge the EV and, when needed, feed power back to the grid, thus supporting grid stability and resilience [1]. In contrast, traditional unidirectional EV chargers (EVCs), which are cost-effective and easy to install and control, have become mainstream infrastructure, facilitating one-way energy flow from the grid to the EV [2]. However, with the large-scale integration of EVs into the grid, issues such as voltage instability, increased load demand, and distribution network overload may arise, impacting power quality with effects like harmonic distortion and voltage drops [2]. In this context, bidirectional charging devices can allocate power more effectively, mitigating the impact of widespread charger integration on the grid and supporting the development of smart grid systems.

2.2 Typical Topologies of Bidirectional Charging Devices for Electric Vehicles

2.2.1 Basic topology of isolated bidirectional DC-DC converters (IBDC)

Compared to traditional non-isolated bidirectional DC-DC converters (NBDC), IBDCs have notable advantages in efficiency and voltage gain. When DC power is converted to AC, transmitted through a high-frequency transformer, and then rectified back to DC, NBDCs are affected by leakage, inductance, and electromagnetic interference, whereas magnetically coupled IBDCs offer higher reliability[3]. IBDCs use high-frequency transformers for power transmission, which provides a higher voltage gain ratio and a broader input range compared to NBDCs. In interactions between EVs and the grid, IBDCs achieve current isolation through the energy storage system (ESS) to meet load demands. Examples include flyback isolated bidirectional converters, Cuk converters, push-pull converters, and forward converters, as shown in Figures 1, Figure 2, Figure 3, and Figure 4.

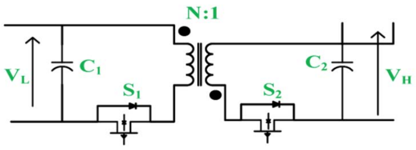

Figure. 1 Flyback isolated bidirectional converters

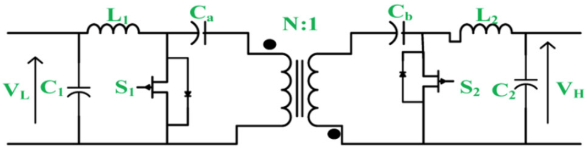

Figure. 2 Cuk converters

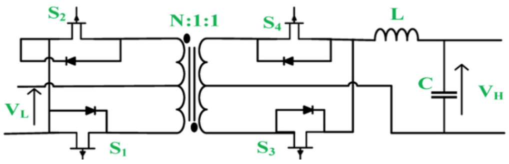

Figure. 3 Push-pull converters

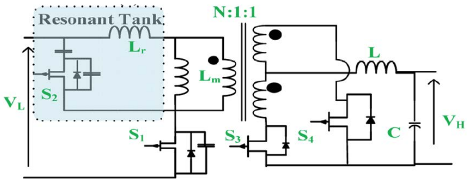

Figure. 4 Forward converters

2.2.2 New multi-port high-gain bidirectional DC-DC converter (NMPHG)

This new type of multi-port high-gain bidirectional DC-DC converter, shown in Figure 5, consists of two input sources and five switches. One of the switches, S_3, controls the energy storage of the storage inductor, while S_1 and S_2 are used to transfer the input voltage from the input sources to the storage inductor. The remaining switches operate in a complementary manner to collectively control the energy transfer of the parallel capacitor. This converter has multiple input and output ports, allowing it to simultaneously connect to various energy sources, such as photovoltaic panels, batteries, and fuel cells. By introducing coupled inductors and a multiphase parallel strategy, this topology enables efficient energy transfer between different voltage levels. The switched capacitor units provide a high boost ratio, making it suitable for energy storage systems requiring a wide range of voltage regulation and allowing multiple energy sources to connect simultaneously, achieving multidirectional power flow across different ports [4].

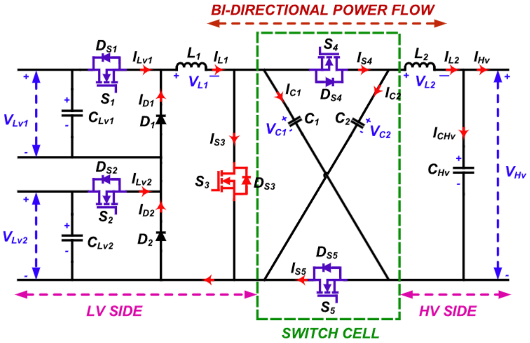

Figure. 5 Multi-Port high-gain bidirectional DC-DC converter

2.2.3 Three-phase bidirectional AC-DC converter

An electric vehicle charging station (EVCS) combining a DSTATCOM (Distribution Static Compensator) dynamic compensation device with a bidirectional AC-DC converter, as shown in Figure 6, enables dynamic regulation of power quality in the distribution network during charging and discharging. This topology utilizes a three-phase AC-DC converter within the charging station, with DSTATCOM providing real-time compensation for grid current harmonics for reactive power management in microgrids [5]. Among various control techniques for parallel active filters, a PI controller optimized by a real-coded genetic algorithm is applied in a three-phase four-wire DSTATCOM [6]. Additionally, a fuzzy extended nondominant sorting genetic algorithm can mitigate power quality issues caused by DSTATCOM in smart grids [7].

For the design of the bidirectional converter, as shown in Figure 7, the input side is integrated with the grid through a filter inductor. Typically, the DC voltage must be sufficiently high to ensure effective dynamic control, but low enough to avoid unnecessary switching losses in the converter. This topology also includes a bidirectional chopper that couples the battery to the AC-DC converter output terminals. The chopper functions as a buck and boost converter during battery charging and discharging [8-11].

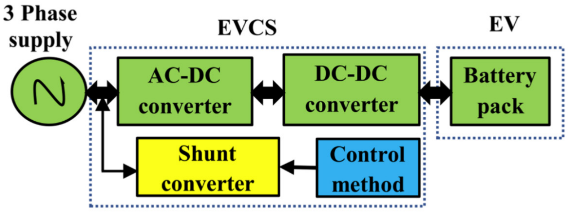

Figure. 6 Sustainable EVCS structure

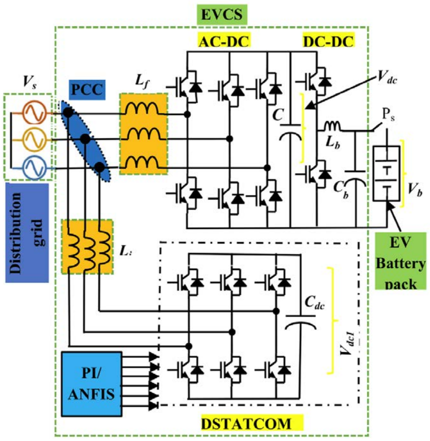

Figure .7 Three-phase bidirectional AC-DC converter

3. Impact of Using Bidirectional Charging Devices on Grid Stability

3.1 Voltage Stability

When a large number of electric vehicles (EVs) are concentrated in a particular area and simultaneously charge or discharge, significant fluctuations in the nodal voltage of the distribution network in that area can occur. EV charging exhibits considerable temporal and spatial distribution variability, especially in parking lots of residential, commercial, and office areas. Due to the randomness and concentration of EV charging, high charging demand during peak hours may lead to severe local voltage stability issues. Additionally, the high instantaneous power demand of fast charging can cause rapid voltage fluctuations, while slow charging may result in prolonged voltage drop effects. Moreover, when EVs feed power back to the grid in V2G mode, voltage may experience a temporary rise, particularly in areas with dense V2G equipment (e.g., commercial parking lots). If V2G mode is improperly managed, it may cause local voltage overshoot, impacting both transient and steady-state stability of the grid.

3.1.1 Grid voltage fluctuations

When a large number of electric vehicles connect to the distribution network for charging or discharging, the randomness and uncertainty of charging and discharging power may cause significant fluctuations in the nodal voltage of the distribution network[12]. Large-scale EV charging can lead to a decrease in nodal voltage, particularly when the EV charging load is high. This voltage drop primarily results from a mismatch between peak charging loads and the capacity of the distribution network. When EVs charge collectively during off-peak hours, the distribution network may become overloaded, causing a substantial voltage drop along the lines, which can reduce the power quality for end users. Studies indicate [13,14] that when EV penetration exceeds a certain threshold, the voltage deviation rate can rapidly increase (exceeding 10%), potentially leading to system instability[15]. If the V2G system fails to effectively manage the charging and discharging of EVs, it may cause substantial local voltage fluctuations, impacting the overall power quality of the grid.

3.1.2 Three-phase voltage imbalance

When a large number of electric vehicles connect to a three-phase distribution network using single-phase charging, any imbalance in the distribution of charging loads across phases can lead to three-phase voltage imbalance, reducing the operational efficiency of the distribution network. As the number of EVs connected increases, the random distribution of single-phase charging loads among the three phases may result in an uneven load distribution, potentially raising the three-phase voltage deviation above the safety threshold set by the distribution network, thus impacting power quality[16]. Additionally, the rapid increase in charging load or the sudden injection of discharging power may cause voltage asymmetry, leading to voltage imbalance within the distribution network, which can affect the operation of transformers and other power equipment[17].

3.2 Harmonic Pollution and Voltage Distortion

Electric vehicle chargers, as nonlinear loads, use rectifiers that are primary sources of harmonics. Different types of chargers (such as six-pulse or twelve-pulse rectifier chargers) generate various harmonic orders and levels, especially during large-scale charging, where these harmonic effects become more pronounced. This harmonic pollution can cause short-term voltage fluctuations in the grid, further impacting grid stability and the safety of other electrical equipment[18]. Studies indicate that converters with different topologies exhibit distinct harmonic characteristics, with isolated converters generally providing better suppression of higher-order harmonics, while non-isolated structures offer advantages in controlling lower-order harmonics. A single-phase onboard charger charging model was developed using MATLAB software. Simulation analysis of the harmonic variation with different numbers of charging electric vehicles shows that as the number of connected EVs increases, the system's total harmonic distortion (THD) of the voltage rises, causing voltage waveform distortion and impacting the overall power quality of the distribution network[19].

3.3 Frequency Stability

3.3.1 Frequency fluctuations

When electric vehicles provide frequency regulation services to the grid via V2G mode, the uncertainty of vehicle charging and discharging and the delay in response time may exacerbate frequency fluctuations. Feeding energy stored in EV batteries back to the grid can cause a sudden increase in grid frequency, particularly when grid load is low (e.g., late at night), where a large number of EVs discharging may lead to a sharp rise in frequency over a short period, potentially resulting in frequency overshoot or oscillation[20]. When multiple bidirectional converters operate simultaneously, response delays may lead to frequency control errors, causing frequency instability. The switching of EVs between G2V (Grid-to-Vehicle) and V2G (Vehicle-to-Grid) modes triggers instantaneous changes in power flow, which may not be detected in real time by the grid's frequency regulation system, leading to delayed frequency regulation.

3.3.2 Impact of reactive power on frequency stability

The charging and discharging behavior of electric vehicles may cause reactive power fluctuations, placing an additional burden on the grid's frequency regulation system. Fluctuations in reactive power not only affect voltage stability but may also induce frequency fluctuations through voltage-frequency coupling. Due to the coupling characteristics of voltage and frequency in the power system, rapid changes in reactive power can lead to nodal voltage fluctuations, which subsequently impact the flow of active power. When EVs switch from G2V mode to V2G mode, the change in power flow direction results in a corresponding change in reactive power demand (e.g., shifting from absorbing reactive power to providing it). If reactive power regulation is not timely or lacks sufficient control precision, it may cause frequency fluctuations in the grid[21].

3.4 Load Fluctuations and Grid Dispatch Pressure

In V2G mode, electric vehicles act as energy storage units participating in power dispatch, effectively alleviating grid load pressure. However, the random charging and discharging behavior of vehicles entering and exiting the system increases the complexity of load forecasting, thus raising the challenges for grid dispatch. Particularly during peak EV charging hours (such as in the evening), if many EVs simultaneously switch from V2G to G2V mode (begin large-scale charging), it will lead to a surge in grid load, requiring the dispatch center to activate backup units to balance the load, thereby increasing dispatch pressure. EV load characteristics also vary significantly across seasons. For example, in summer and winter, due to higher electricity consumption from air conditioning (for cooling and heating), the amplitude of EV load fluctuations during charging and discharging is considerably higher than in spring and autumn. In winter, as battery efficiency decreases significantly in low temperatures, the charging demand of EVs increases, which prolongs their response time in V2G mode, further complicating the grid's load fluctuation management[22].

4. Targeted Optimization Strategies

4.1 Voltage Stability Optimization Strategies

4.1.1 Hierarchical control and dynamic voltage regulation

Hierarchical Control: Voltage control is divided into three levels: local, regional, and global control.Responsible for voltage regulation of individual charging stations or electric vehicles. This layer's control objectives focus primarily on ensuring safe charging for individual devices, preventing the effects of instantaneous power fluctuations on the equipment itself, and responding to local grid dispatch signals when necessary. Conducts coordinated control of multiple vehicles through an aggregator. Acting as an intermediate layer, the aggregator collects status information from multiple charging stations or electric vehicles and optimizes the scheduling of voltage states and power demands within the region to mitigate voltage fluctuations in the local grid. Performs integrated scheduling and strategy formulation based on the overall voltage state of the grid. The global layer is responsible for higher-level grid frequency and voltage regulation, typically ensuring overall grid stability through extensive coordinated control of charging and discharging.

By introducing a Dynamic Voltage Restorer (DVR) in electric vehicle charging stations, as shown in Figure 8, this device is primarily used to compensate for voltage fluctuations caused by events such as voltage sag, voltage swell, and voltage flicker. The main working principle of the DVR is that, during a voltage dip in the grid, the DVR quickly injects a compensating voltage through its internal voltage source inverter that matches the amount of the voltage drop, thereby restoring the system voltage to a normal level within a few milliseconds after the voltage anomaly occurs.

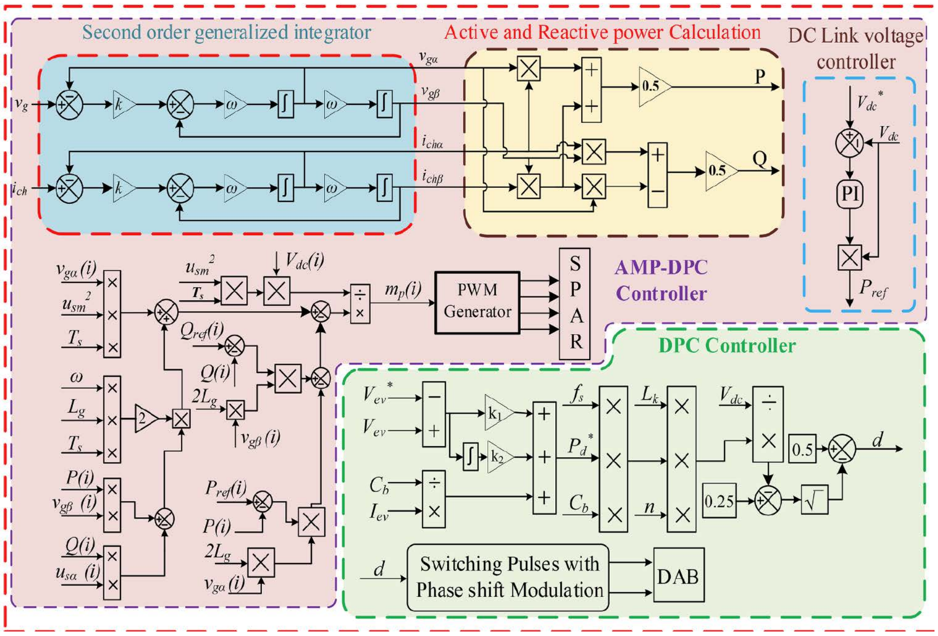

Figure. 8 Dynamic voltage restorer control strategy

4.1.2 Dynamic reactive power compensation

To suppress voltage fluctuations, a Distributed Static Synchronous Compensator (DSTATCOM) is used to compensate for reactive power, enabling rapid reactive power adjustment when voltage fluctuations occur due to EV charging and discharging behavior, thereby ensuring stability of nodal voltage. DSTATCOM dynamically adjusts reactive power output to balance voltage, eliminating voltage instability caused by load changes. DSTATCOM's role is to respond quickly to grid voltage fluctuation signals (such as voltage sag or swell triggered by large-scale charging or discharging) and adjust reactive power output and absorption within a few milliseconds, allowing the grid voltage to return to a stable state in a short time. The control strategy is shown in Figure 9.

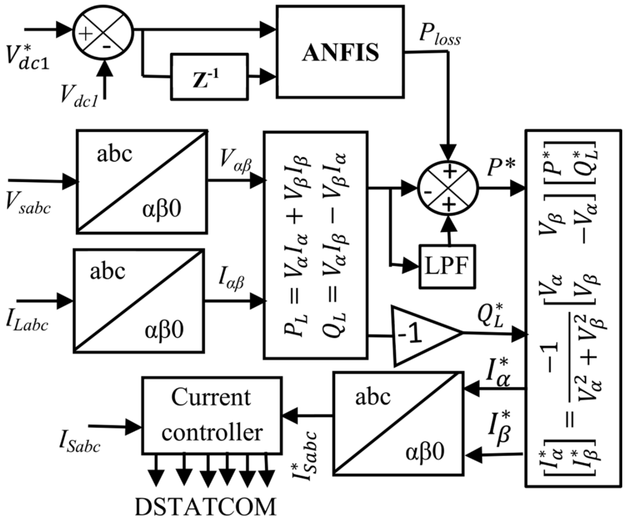

Figure. 9 DSTATCOM control strategy

4.1.3 Multi-port high-gain bidirectional converter

Using a multi-port high-gain topology design enables more efficient energy conversion between different voltage levels, thereby reducing voltage fluctuations under various load conditions and enhancing overall system voltage stability. As shown in Section 2.2 of this paper, the multi-port bidirectional converter allows dynamic regulation of energy flow between high voltage (HV) and low voltage (LV) modes, helping to reduce voltage fluctuations during load changes. By dynamically adjusting the operating mode of each input port (e.g., switching between parallel or series inductor configurations), voltage stability can be maintained when there is a sudden increase or decrease in load. This design is especially suitable for EV charging and discharging systems, effectively minimizing voltage fluctuations under varying load demands. Its high-gain characteristics and multi-port configuration significantly improve voltage conversion efficiency.

4.2 Frequency Stability Optimization Strategies

4.2.1 Model predictive control

Frequency control strategies based on Model Predictive Control (MPC) allow for real-time monitoring of grid frequency states and predictive analysis of future frequency trends, enabling proactive adjustment of EV charging and discharging behaviors. This approach provides rapid responses to frequency fluctuations, reducing instability caused by load fluctuations. The model begins by establishing a mathematical representation of the system to describe the impact of EV charging and discharging on grid frequency and voltage. By continuously monitoring system states (such as voltage, current, and power), it predicts system states over multiple future time points. The optimization goal is to minimize frequency deviation and voltage fluctuation while ensuring that EV users' charging needs are not excessively compromised.

This is achieved using a rolling optimization strategy, where the optimization problem is recalculated at each sampling interval, applying the control input for the immediate time step. This ensures the system consistently employs optimal control strategy in response to load fluctuations and grid state changes. MPC is widely used in power systems for dynamic frequency and voltage control, especially in EV-to-grid interactions. Given the bidirectional energy flow capability of EVs in V2G (Vehicle-to-Grid) mode, MPC can effectively predict and adjust frequency fluctuations during rapid switching in the power flow direction. Main applications include the following scenarios:

Frequency Stability Adjustment during Sudden Load Changes: When electric vehicles switch between different charging modes (G2V and V2G), there is a significant change in power flow within the system. MPC can predict instantaneous load variations and adjust charging and discharging power within seconds to prevent large frequency fluctuations.

Frequency Response Optimization for Distributed Electric Vehicles: When a large number of EVs are connected simultaneously, MPC can optimize global frequency regulation strategies by coordinating the charging and discharging behavior of multiple charging stations and EVs, thereby enhancing the overall frequency stability of the system.

4.2.2 Distributed frequency regulation strategy

Using electric vehicles as distributed energy storage units to coordinate frequency regulation across multiple levels.

Local Frequency Regulation: Individual charging stations respond to local grid frequency fluctuations by adjusting the charging and discharging power of electric vehicles.

Global Frequency Coordination: Coordinating the discharging behavior of EV charging stations across multiple regions to respond to global frequency changes, thereby avoiding broader frequency fluctuations caused by inconsistent local responses.

4.2.3 Vehicle-to-grid (V2G) assisted frequency regulation

Orderly Discharge Strategy: During peak load periods, electric vehicles are guided to feed power back to the grid through V2G mode, reducing peak load pressure on the grid and stabilizing frequency fluctuations.Multi-Level Response Strategy: Based on grid frequency deviation, electric vehicles participate in frequency regulation at different levels (such as primary and secondary frequency regulation), gradually mitigating frequency fluctuations in a tiered manner. This strategy offers faster response times and improved coordination.

4.3 Load Fluctuation and Dispatch Pressure Optimization Strategy

4.3.1 Demand response mechanism

Using price incentives and load management strategies, electric vehicle users are encouraged to charge during off-peak hours and discharge during peak hours, achieving peak shaving and valley filling. By dynamically adjusting users' charging and discharging times and power, this approach effectively alleviates peak load pressure on the grid, balances supply-demand discrepancies and reduces the complexity of grid dispatch. V2G technology enables demand response to balance grid supply and demand; during peak demand, EVs can discharge via V2G to provide auxiliary support, easing grid pressure, while during off-peak hours, EVs can orderly charge, filling in the demand valley. The core of the demand response mechanism is to guide EVs in orderly charging and discharging across different time periods through dynamic price signals and market-based control methods. For instance, during high-demand periods, EV users can receive incentives for discharging to meet grid demand, participating in frequency regulation and power quality optimization.

4.3.2 Peak shaving and valley filling strategy

During peak demand periods (typically in the evening), uncoordinated EV charging may cause a rapid rise in grid load, resulting in local distribution grid overload and voltage drops. During peak grid load periods, some EVs are encouraged to delay charging or switch to V2G mode to feed power back to the grid, reducing load pressure during high-demand times and preventing voltage fluctuations and overloads in the distribution network. During off-peak periods (such as late at night), EV charging is incentivized through lower electricity rates or economic rewards, encouraging concentrated charging during these times to fill in the load valley. This strategy also effectively improves grid utilization and reduces voltage fluctuations caused by load imbalances.

4.4 Intelligent Optimization and Control Strategy

4.4.1 Hybrid optimization algorithm (PSO and GA)

Combining Particle Swarm Optimization (PSO) and Genetic Algorithm (GA): In multi-objective optimization (e.g., power quality, system efficiency, frequency stability), intelligent optimization algorithms dynamically adjust control parameters to enhance system stability. This control strategy optimizes the control parameters of all controllers in a bidirectional EV charging system (such as voltage controllers, current controllers, and battery current controllers), minimizing DC-Link voltage error and battery current error in the bidirectional power electronics device during EV charging and discharging modes [9-11].

4.4.2 Real-time intelligent control

Using artificial intelligence techniques (such as neural networks and machine learning) for real-time optimization control, this approach adapts to the complex charging and discharging behaviors under different operating conditions. A real-time intelligent control strategy establishes a communication and information exchange system between vehicles and the grid, allowing real-time monitoring of vehicle status (e.g., battery condition, remaining power, estimated parking time) and dynamically adjusting EV charging and discharging strategies based on grid load requirements, thus achieving bidirectional energy flow between the grid and EVs. Specific applications include:

During peak load periods, by monitoring grid load status and EV power demands in real time, the system dynamically adjusts each vehicle's discharging power to provide the necessary load support for the grid without affecting vehicle range requirements. During off-peak periods, by predicting future load conditions, the intelligent control system can schedule EV charging in advance, achieving "peak shaving and valley filling" and reducing the grid's peak-to-valley difference.

5. Conclusion

This study provides an in-depth analysis of bidirectional charging devices for electric vehicles, particularly focusing on their role in enhancing grid stability. Traditional unidirectional charging models struggle to handle the load pressure on the grid from large-scale EV integration. Bidirectional charging devices, utilizing V2G and G2V technologies, not only offer efficient charging but also feed power back to the grid during peak loads, balancing grid demand. Research indicates that bidirectional charging devices significantly improve grid voltage and frequency stability, effectively suppressing voltage fluctuations and harmonic distortion, and alleviating instantaneous load stress during peak periods.

The study analyzes various topologies of bidirectional power electronic converters, finding that isolated bidirectional DC-DC converters (IBDC) offer advantages in energy conversion efficiency and voltage gain, reducing electromagnetic interference and leakage inductance effects. Additionally, new multi-port high-gain converters exhibit efficient voltage conversion and flexibility in multi-energy storage systems. Regarding intelligent control, this study explores the application of hybrid optimization algorithms and Model Predictive Control (MPC). These control methods dynamically adjust EV charging and discharging behavior by monitoring grid status in real time, ensuring grid stability under high loads.

In the future, with the widespread adoption of EVs and their bidirectional charging devices, the operational model of power systems will fundamentally change. EVs will not only act as power consumers but also as energy storage and generation resources through bidirectional power flow. However, the challenges to grid stability posed by random connections and large-scale usage will require more efficient converters, intelligent control, and coordinated optimization with renewable energy. Bidirectional charging devices will become key regulatory resources in future smart grids, supporting the global transition to green energy.

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