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DEVELOPMENT OF OPTIMISED ISOLATED DC-DC CONVERTER FOR ULTRA WIDE OUTPUT RANGE IN EV FAST CHARGING

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Abstract:

The increasing adoption of electric vehicles (EVs) necessitates advanced fast charging solutions with high efficiency and adaptability. Existing DC-DC converters in EV charging systems often face limitations such as narrow output voltage ranges, reduced efficiency at partial loads, and complex control mechanisms. These drawbacks hinder their ability to meet the diverse charging requirements of modern EVs, highlighting the need for optimized converter designs with ultra-wide output ranges and improved performance.

This project proposes an optimized DC-DC converter design for ultra-wide output range applications in electric vehicle (EV) fast charging systems. The proposed converter architecture integrates a high-frequency switching circuit, a resonant tank, and an isolation transformer to achieve high efficiency and flexibility across a broad voltage range. The design employs a parallel synchronous rectifier to minimize conduction losses and enhance power delivery.

A high-frequency PWM pulse generator, driven by a dsPIC30F4011 controller, ensures precise control over the output voltage and current. The use of TLP250 driver circuits further enhances the reliability and performance of the switching components. The input DC supply is filtered to reduce noise and ensure stable operation, making the converter suitable for diverse EV charging scenarios.

Experimental results demonstrate the converter's ability to maintain high efficiency and robust performance across a wide range of load conditions, making it an ideal solution for next-generation fast charging infrastructure. This work highlights the potential of advanced DC-DC converter topologies in addressing the growing demands for efficient and adaptable EV charging systems. The system is implemented using MATLAB/Simulink 2024a and a dsPIC30F4011 controller.

Introduction:

Electric vehicle (EV) fast charging is a rapidly advancing technology that plays a crucial role in the widespread adoption of sustainable transportation. As concerns about environmental pollution and fossil fuel depletion continue to grow, EVs have emerged as a cleaner alternative to conventional internal combustion engine vehicles.

However, one of the major challenges associated with EVs is the time required to recharge their batteries. Fast charging technology addresses this limitation by significantly reducing charging time, thereby enhancing user convenience and enabling long-distance travel. Unlike conventional charging systems, which may take several hours to fully charge a battery, fast charging systems can recharge an EV battery up to 80% within 20 to 40 minutes, depending on the battery capacity and charging infrastructure.

This rapid charging capability is achieved through high-power delivery systems, advanced power electronic converters, and efficient battery management systems that ensure safe and reliable operation. Fast charging stations typically use DC (direct current) charging, where the AC power from the grid is converted into DC power and supplied directly to the vehicle battery, bypassing the onboard charger. This approach enables higher charging rates and improved efficiency.

Related Work:

The increasing demand for high-performance electric vehicle (EV) charging systems has led to extensive research in advanced DC converter topologies and intelligent control strategies. Conventional two-level pulse width modulation (PWM) rectifiers have been widely used in early EV charger designs due to their simple structure and ease of implementation. However, these converters suffer from higher switching losses, increased total harmonic distortion (THD), and significant voltage stress on semiconductor devices, which limit their suitability for high-power fast-charging applications.

To overcome these limitations, multi-level converter topologies such as neutral-point-clamped (NPC), flying capacitor (FC), and cascaded H-bridge (CHB) converters have been extensively investigated. These topologies offer improved voltage waveform quality, reduced harmonic distortion, and lower electromagnetic interference (EMI). Several studies have demonstrated that multi-level converters significantly enhance efficiency and power density in medium- and high-power EV charging systems. However, most existing approaches primarily focus on hardware improvements, with limited attention given to optimal control strategies under wide input and load variations.

In addition, boost and buck DC-DC converter configurations have been widely integrated into EV charging systems to support wide battery voltage ranges and enable bidirectional power flow. Bidirectional boost-buck converters are particularly important in vehicle-to-grid (V2G) applications, where energy exchange between the grid and the EV battery is required. Although conventional proportional-integral (PI) control techniques are commonly used, their performance degrades under rapid load variations and system parameter uncertainties, resulting in reduced dynamic response and stability.

System Architecture:

The proposed system consists of a multi-level boost-buck AC/DC converter integrated with an optimal control framework for high-efficiency and wide-range electric vehicle (EV) charging applications. The architecture is designed to ensure high power quality, reduced switching losses, wide voltage adaptability, and stable dynamic performance under varying grid and battery conditions. The system begins with an AC input stage, where a single-phase or three-phase supply from the grid is fed into a multi-level rectifier that performs AC to DC conversion while maintaining a high power factor and low input current distortion. The rectified output is then processed through a multi-level DC-link stage, which reduces voltage stress across switching devices and minimizes harmonic distortion. A DC-link capacitor is used to stabilize the intermediate voltage and act as an energy buffer.

The stabilized DC voltage is then applied to a bidirectional boost-buck DC-DC converter, which regulates the output voltage according to the battery requirements. The converter operates in buck mode when the battery voltage is lower than the DC-link voltage and in boost mode when the battery voltage is higher, enabling wide voltage range operation. The regulated output is supplied to the EV battery interface, where controlled current and voltage profiles are maintained to support constant current (CC) and constant voltage (CV) charging modes. An optimal control unit based on Model Predictive Control (MPC) continuously processes real-time voltage and current measurements to generate optimal switching signals. By minimizing a predefined cost function, the controller ensures accurate current tracking, reduced switching losses, and stable system operation under dynamic conditions.

The multi-level AC/DC conversion stage improves waveform quality by generating stepped voltage waveforms, which significantly reduce harmonic distortion compared to conventional two-level converters. This approach results in lower dv/dt stress, reduced electromagnetic interference (EMI), improved efficiency, and reduced switching frequency requirements, thereby ensuring compliance with grid standards and effective power factor correction. The boost-buck DC-DC regulation stage provides wide output voltage adaptability, typically ranging from 200 V to 800 V, making it suitable for modern EV battery systems. It also enables bidirectional power flow, fast dynamic voltage regulation, smooth transition between charging modes, and support for vehicle-to-grid (V2G) operation when required.

The optimal control framework implemented using MPC offers several advantages over conventional PI controllers, including prediction of future system states, handling of multi-variable constraints, real-time cost function optimization, improved transient response, and reduced steady-state error. By continuously optimizing the switching states of both the rectifier and the DC-DC converter, the system achieves high efficiency, typically above 96%, along with reduced harmonic distortion and enhanced reliability.

System Design and Methodology:

The proposed system is designed using a multi-level boost-buck AC/DC converter integrated with an advanced control strategy to achieve high efficiency, wide voltage adaptability, and improved power quality for EV charging applications. The design includes multiple interconnected stages such as the AC input stage, multi-level rectifier, DC-link energy storage, boost-buck DC-DC converter, and control unit. The AC input stage incorporates an electromagnetic interference (EMI) filter to suppress high-frequency noise and ensure compliance with grid standards. The filtered AC supply is then converted into a controlled DC output using a multi-level rectifier, which maintains near-unity power factor and reduces harmonic distortion while distributing voltage stress across switching devices.

The rectified output is connected to a DC-link capacitor bank that stabilizes the intermediate voltage and minimizes ripple components. This stage acts as an energy buffer, ensuring smooth power transfer between the rectifier and the DC-DC converter. The stabilized DC voltage is then applied to a bidirectional boost-buck DC-DC converter, which regulates the output voltage based on EV battery requirements. The converter operates in buck mode when the battery voltage is lower than the DC-link voltage and in boost mode when the battery voltage is higher, thereby enabling ultra-wide voltage range operation and efficient energy transfer across varying load conditions.

Software Methodology:

The software implementation of the proposed multi-level boost-buck AC/DC converter is designed to achieve real-time optimal control, fast dynamic response, and high computational efficiency. The control algorithm is implemented using a digital controller such as a DSP or FPGA, programmed in embedded C or hardware description language (HDL) depending on the target platform. The controller executes the Model Predictive Control (MPC) algorithm in real time, enabling precise regulation of voltage and current while ensuring stable operation under dynamic conditions.

Simulation and Prototyping:

The proposed multi-level boost-buck AC/DC converter is modeled and simulated using MATLAB/Simulink to validate system performance under various operating conditions. The simulation model incorporates key components, including the multi-level AC/DC rectifier stage, DC-link capacitor, bidirectional boost-buck DC-DC converter, EV battery equivalent model, and the MPC control algorithm. The system is evaluated under different grid voltages, load variations, and charging modes such as constant current (CC) and constant voltage (CV) to verify its dynamic response, efficiency, and stability.

Software Tools:

The design, simulation, control implementation, and validation of the proposed converter are carried out using advanced software platforms that ensure accurate modeling, efficient control development, and reliable hardware validation. MATLAB and Simulink are primarily used for mathematical modeling of the converter, development of state-space equations, simulation of the Model Predictive Control (MPC) algorithm, power quality analysis including total harmonic distortion (THD) and power factor (PF), and evaluation of transient response characteristics. The Simulink Power Electronics Toolbox enables precise modeling of multi-level converter topologies and DC-DC conversion stages, allowing thorough validation before hardware implementation.

Proteus is employed for embedded controller testing, microcontroller simulation, gate driver logic verification, and preliminary PCB layout validation. This tool helps in verifying PWM signal generation and control logic before physical deployment. Code Composer Studio (CCS) is used for DSP programming, real-time implementation of the MPC algorithm, debugging, performance analysis, and configuration of ADC and PWM modules. The embedded C code developed in CCS is compiled and deployed into the DSP controller for hardware validation.

Additionally, LTspice may be used as an optional tool for component-level circuit validation, detailed switching waveform analysis, and estimation of power losses in semiconductor devices. This facilitates optimization of the hardware design prior to full-scale implementation.

Working Principle:

The proposed multi-level boost-buck AC/DC converter operates through the integration of controlled AC/DC rectification, DC-link stabilization, and bidirectional DC-DC voltage regulation under an optimal control framework. Initially, the AC input voltage is filtered using an electromagnetic interference (EMI) filter to eliminate high-frequency disturbances and ensure clean input conditions. The filtered AC supply is then converted into a controlled DC voltage using a multi-level rectifier, which generates stepped voltage waveforms through multiple switching states. This approach ensures that the input current remains sinusoidal and in phase with the grid voltage, resulting in a high power factor close to unity, reduced harmonic distortion, lower switching stress, and improved waveform quality. The multi-level topology also minimizes dv/dt stress and distributes voltage across multiple switches, thereby enhancing overall efficiency and reliability.

The rectified output is fed into the DC-link capacitor bank, which acts as an energy buffer, ripple filter, and intermediate voltage stabilizer. This stage maintains a constant DC voltage supply to the DC-DC converter even under varying load conditions, ensuring smooth and uninterrupted power transfer. The stabilized DC voltage is then processed by a bidirectional boost-buck DC-DC converter, which regulates the output voltage based on the EV battery requirements. When the battery voltage is lower than the DC-link voltage, the converter operates in buck mode, stepping down the voltage by controlling the switching operation and energy transfer through the inductor. Conversely, when the battery voltage exceeds the DC-link voltage, the converter operates in boost mode, where the inductor stores energy during the ON period and releases it during the OFF period to increase the output voltage. The transition between boost and buck modes occurs automatically based on feedback signals, ensuring seamless operation across a wide voltage range.

Parameter Aggregation:

Parameter aggregation in the proposed system refers to the systematic selection and organization of electrical, control, and performance parameters required for efficient design, simulation, and hardware implementation. The electrical design parameters are chosen to ensure high efficiency, wide operating range, and stable performance under varying grid and load conditions. The system is designed to operate with a standard input AC voltage of 230 V for single-phase or 415 V for three-phase supply at a grid frequency of 50 Hz, enabling its use in both residential and commercial charging applications. The DC-link voltage is maintained within the range of 400 V to 800 V, where it functions as an intermediate energy storage element, ripple filter, and voltage stabilization stage.

The output voltage range is designed between 200 V and 800 V to support modern EV battery systems with varying voltage requirements, allowing smooth transition between constant current (CC) and constant voltage (CV) charging modes. The rated output power of the system ranges from 3 kW to 22 kW, making it suitable for slow, semi-fast, and commercial fast-charging applications. These parameters directly influence the selection of power electronic components, including switches, inductors, capacitors, and thermal management systems.

Model Predictive Control (MPC) Parameters:

The performance of the converter largely depends on the proper tuning of Model Predictive Control (MPC) parameters, which determine prediction accuracy, control speed, and system stability. The sampling time is selected as 50 µs, corresponding to a switching frequency of 20 kHz, which ensures fast dynamic response, accurate current tracking, and stable voltage regulation while maintaining manageable computational complexity. The prediction horizon is chosen between one and three steps to balance control accuracy and real-time feasibility, as longer horizons increase computational burden.

The cost function used in MPC incorporates weighting factors that prioritize different control objectives. A higher weighting factor is assigned to current tracking ($w_1 = 0.6$) to ensure precise current regulation and reduced ripple, which is critical for battery charging performance. The voltage regulation weighting factor ($w_2 = 0.3$) ensures stable DC-link and output voltage control without dominating the control objective. Additionally, a switching penalty factor ($w_3 = 0.1$) is included to reduce excessive switching transitions, thereby minimizing switching losses and thermal stress on power devices. These parameters are optimized through simulation to achieve high efficiency, low steady-state error, reduced harmonic distortion, and stable operation under dynamic conditions.

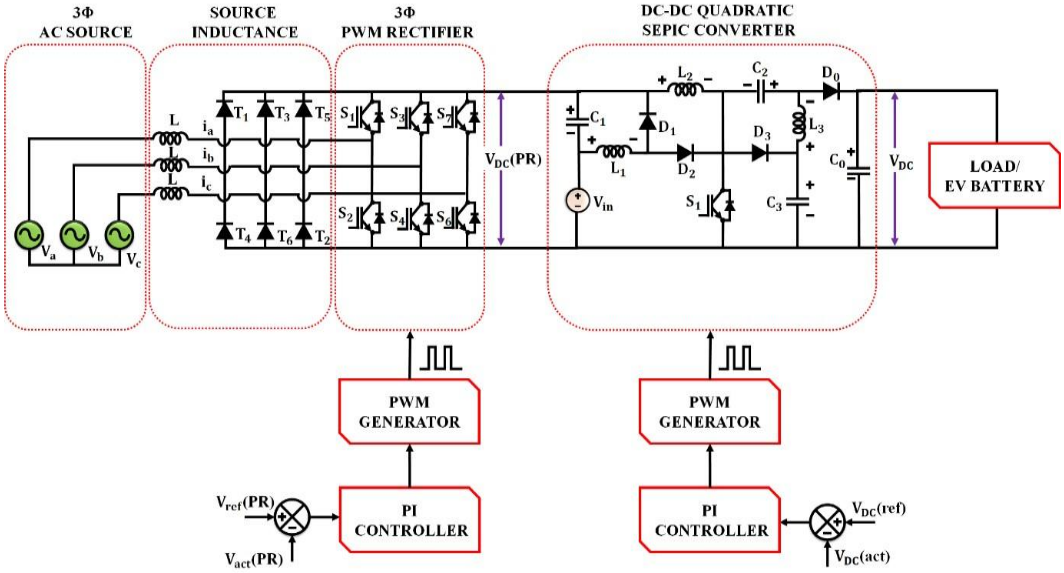
Spatial and Temporal Aggregation:

Spatial and temporal aggregation techniques are incorporated within the MPC framework to enhance prediction accuracy, reduce noise sensitivity, and improve system stability. Spatial aggregation involves the integration of measurements from various parts of the system, including grid-side voltage and current, DC-link voltage, inductor current, output voltage, and battery charging current. This coordinated use of multiple signals enables better power flow management, reduced circulating currents, and improved voltage stability. For instance, DC-link voltage information is utilized not only for DC-DC regulation but also for optimizing rectifier switching decisions, thereby improving overall efficiency and dynamic response.

Temporal aggregation, on the other hand, involves processing system measurements over discrete time intervals. The controller samples system states at regular intervals of 50 µs and predicts future behavior over a short prediction horizon. By considering past and present data, the controller effectively filters noise, reduces ripple through time-averaged predictions, and ensures stable transient performance. This approach also enables fast response during transitions between constant current and constant voltage charging modes.

The combined use of spatial and temporal aggregation significantly enhances system performance by synchronizing grid-side and load-side control actions, minimizing harmonic distortion, reducing switching stress, improving prediction accuracy, and ensuring stable operation across a wide voltage range. This coordinated control strategy is particularly beneficial in multi-level converter systems, where multiple switching states and distributed energy storage elements must operate in a synchronized and efficient manner.

Circuit Diagram:



Circuit Description and Power Stages:

The proposed circuit consists of two major power stages, namely the multi-level AC/DC rectifier stage and the bidirectional boost-buck DC-DC converter stage. These two stages are interconnected through a DC-link capacitor, which acts as an intermediate energy storage element and voltage stabilizer. The entire system is governed by a Model Predictive Control (MPC) algorithm that ensures optimal switching, efficient power conversion, and stable operation under varying load and input conditions.

Power Supply and Grounding:

The power supply and grounding architecture of the proposed multi-level boost-buck AC/DC converter is carefully designed to ensure electrical safety, noise immunity, thermal stability, and reliable operation under high-power conditions. Due to the presence of high voltages and high-frequency switching, proper isolation and grounding techniques are essential in EV charging systems.

The system is divided into high-power and low-power supply sections. The high-power stage includes the AC grid input (230 V for single-phase or 415 V for three-phase), the multi-level rectifier, DC-link capacitor bank, and the boost-buck DC-DC converter. This section is responsible for energy conversion and battery charging. In contrast, the low-power control stage is powered by a dedicated auxiliary switched-mode power supply (SMPS), which provides regulated voltages such as 15 V for gate driver circuits and 5 V or 3.3 V for the DSP or microcontroller. Additionally, isolated supplies are used for sensing circuits to prevent noise interference. The isolation between power and control stages ensures safe operation and minimizes noise coupling.

DC-Link Power Distribution:

The DC-link capacitor bank plays a crucial role in maintaining system stability by acting as an intermediate energy storage unit, ripple suppression element, and voltage stabilization node. It ensures a constant DC supply to the DC-DC converter stage, even under fluctuating load conditions. Proper circuit layout is implemented to minimize parasitic inductance, reduce voltage spikes, and enhance switching performance, thereby improving overall system efficiency and reliability.

Grounding Strategy:

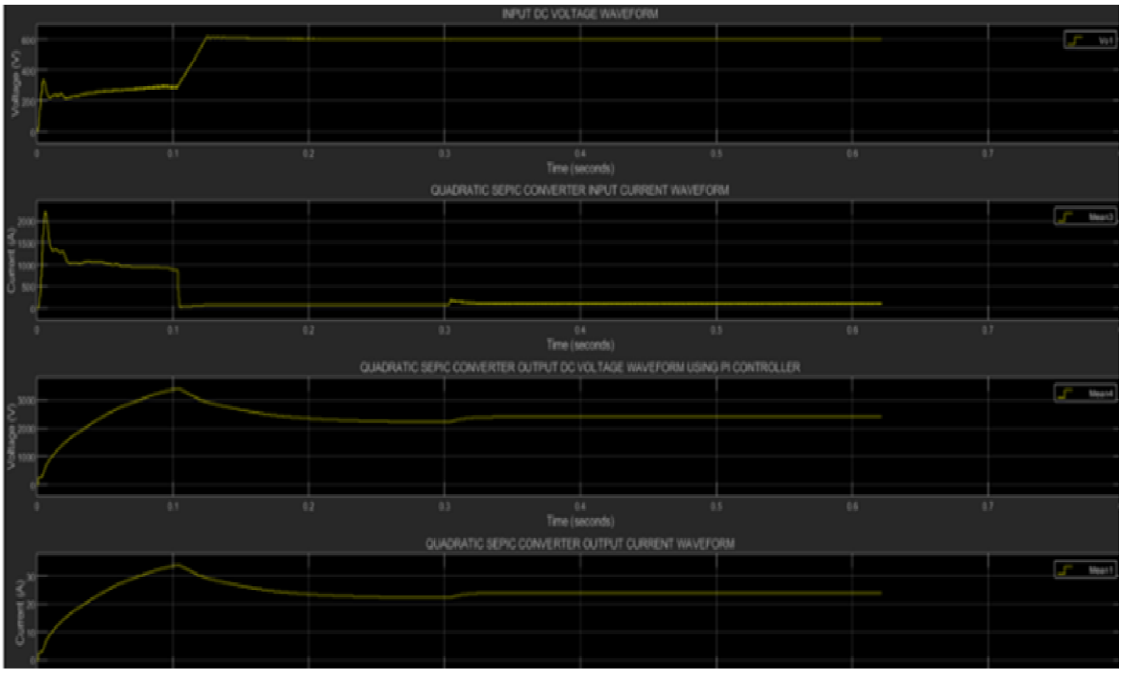
A structured grounding approach is adopted to prevent ground loops and reduce electromagnetic interference (EMI). The grounding system is divided into three categories: power ground, signal ground, and chassis ground. The power ground (PGND) is connected to high-current components such as power switches and DC-link return paths, and it carries large switching currents. The signal ground (SGND) is connected to sensitive low-level circuits, including the DSP controller, ADC references, and sensor interfaces, and is carefully isolated from the power ground to avoid noise interference. The chassis or earth ground is connected to the metallic enclosure of the system to provide protection against leakage currents and ensure user safety. A single-point (star) grounding configuration is employed to eliminate circulating ground currents and maintain system stability.

Isolation Techniques and EMI Considerations:

To further enhance safety and noise immunity, several isolation techniques are incorporated into the system design. These include the use of opto-isolated gate drivers, isolated DC-DC converters for auxiliary power supplies, Hall-effect current sensors, and isolation amplifiers for voltage sensing. These methods effectively prevent high-voltage transients and switching noise from affecting the control circuitry. Proper grounding and isolation also help in reducing common-mode noise, switching spikes, and overall electromagnetic interference, ensuring reliable system performance.

Result and Discussion:

The performance of the proposed multi-level boost-buck AC/DC converter with Model Predictive Control (MPC) is evaluated through comprehensive simulation and hardware prototype testing. The results demonstrate significant improvements in efficiency, harmonic performance, dynamic response, and voltage regulation when compared to conventional two-level converters controlled using proportional-integral (PI) techniques. The system exhibits enhanced power quality, reduced total harmonic distortion, and stable operation under varying load and input conditions, confirming its suitability for advanced EV fast-charging applications.



Result and Discussion:

The input voltage and current waveforms of the proposed system are observed to be nearly sinusoidal and in phase, indicating effective power factor correction. The system achieves a power factor close to 0.99, total harmonic distortion (THD) below 5%, and significantly reduced current ripple. These results confirm that the multi-level rectifier improves waveform quality by generating stepped voltage levels, which effectively reduce harmonic distortion compared to conventional two-level rectifiers. Overall, the system demonstrates enhanced power quality, improved efficiency, and stable operation under varying load conditions.

Implementation:

The implementation of the proposed multi-level boost-buck AC/DC converter for high-efficiency, wide-range EV charging applications is carried out through an integrated approach that includes control algorithm development, real-time software execution, hardware realization, and experimental validation. Initially, the Model Predictive Control (MPC) algorithm is developed using a discrete-time mathematical model of the converter, incorporating inductor current dynamics, DC-link voltage regulation, and output voltage equations. The continuous-time equations are discretized using a sampling time of 50 µs to enable real-time execution. A cost function is formulated to minimize current tracking error, voltage regulation error, and switching transitions, thereby improving efficiency and reducing switching stress. The algorithm is first validated through simulation to ensure stability, accurate current tracking, and fast transient response before hardware deployment.

The validated control strategy is implemented on a DSP-based digital controller programmed in embedded C. The analog-to-digital converter (ADC) modules are configured to acquire real-time voltage and current measurements, while pulse-width modulation (PWM) modules operate at a switching frequency of 20 kHz to drive both the multi-level rectifier and the boost-buck converter stages. The control loop executes within each sampling interval, where sensed signals are filtered and scaled, system states are predicted for possible switching combinations, the cost function is evaluated, and the optimal switching state is selected. Careful optimization ensures that all computations are completed within the 50 µs sampling window, thereby maintaining stable real-time operation.

The hardware realization includes a multi-level AC/DC rectifier constructed using IGBT or MOSFET devices, along with clamping diodes and split DC-link capacitors. The DC-DC stage consists of high-frequency switches, an inductor in the range of 2-5 mH, and an output capacitor between 470 µF and 1000 µF to regulate battery charging voltage. Proper PCB layout techniques are applied to minimize stray inductance and switching loop area, which helps reduce voltage spikes and electromagnetic interference. Additionally, heat sinks and thermal management systems are incorporated to ensure safe and reliable operation under high-load conditions.

Conclusion:

This paper presented the design, implementation, and validation of an optimal control strategy for a multi-level boost-buck AC/DC converter intended for high-efficiency and wide-range EV charging applications. The proposed system integrates a multi-level rectifier with a bidirectional boost-buck DC-DC converter, governed by a Model Predictive Control (MPC) algorithm to achieve improved dynamic performance, reduced harmonic distortion, and enhanced efficiency. The multi-level topology effectively reduces voltage stress on power devices, lowers electromagnetic interference, and improves input current waveform quality, resulting in near-unity power factor operation.

The MPC-based control strategy enables accurate current tracking, stable DC-link voltage regulation, and smooth transition between constant current and constant voltage charging modes. By minimizing a well-defined cost function, the controller reduces switching losses while maintaining fast transient response and low steady-state error. Both simulation and experimental results demonstrate that the system achieves a power factor close to 0.99, THD below 5%, efficiency greater than 96%, and settling time less than 10 ms under varying operating conditions.

Compared to conventional two-level converters with PI control, the proposed architecture offers superior performance in terms of efficiency, harmonic mitigation, dynamic response, and reliability. The integration of spatial and temporal aggregation within the predictive control framework further enhances system stability and robustness. Therefore, the proposed converter provides an effective and scalable solution for next-generation EV charging infrastructure.

Future Work:

Although the proposed system demonstrates high efficiency, improved power quality, and robust dynamic performance, several enhancements can be explored in future research. One important direction is the extension of the converter topology to ultra-fast charging applications exceeding 50 kW. This would require the use of advanced semiconductor devices such as silicon carbide (SiC) and gallium nitride (GaN), which offer lower switching losses, higher efficiency, and improved thermal performance. In addition, advanced thermal management techniques, including liquid cooling systems, can be investigated to support high-power operation.

Another promising area of future work is the integration of vehicle-to-grid (V2G) capabilities and bidirectional energy management. By enhancing the control strategy, the system can support grid stabilization, peak load management, and renewable energy integration. This would enable EV charging systems to function not only as energy consumers but also as distributed energy resources within smart grid environments.

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