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OPTIMAL CONTROL OF MULTI-LEVEL BOOST-BUCK AC/DC CONVERTER FOR HIGH EFFICIENCY, WIDE-RANGE EV CHARGERS

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Abstract:

The rapid growth of electric vehicles (EVs) demands high-efficiency, wide-range charging systems capable of operating under varying grid and battery conditions. This paper presents the optimal control of a multi-level boost-buck AC/DC converter designed for high-performance EV chargers. The proposed topology integrates a multi-level rectification stage with a bidirectional boost-buck DC-DC conversion unit to achieve improved power factor, reduced harmonic distortion, and enhanced voltage regulation. An advanced optimal control strategy based on model predictive control (MPC) is implemented to ensure dynamic response, minimized switching losses, and stable operation across a wide input voltage range. The multi-level configuration significantly reduces voltage stress on power devices and lowers electromagnetic interference while improving overall conversion efficiency. The system is capable of handling both fast-charging and normal-charging modes, making it suitable for residential and commercial EV charging stations. Simulation results demonstrate high efficiency above 96%, reduced total harmonic distortion (THD), and robust performance under load variations. Comparative analysis with conventional two-level converters confirms the superiority of the proposed approach in terms of efficiency, power density, and control flexibility. The developed optimal control scheme enhances reliability and extends battery life by ensuring precise current and voltage regulation. Therefore, the proposed multi-level boost-buck AC/DC converter provides an effective and scalable solution for next-generation wide-range EV charging applications.

Key Words: Electric Vehicle (EV) Charger, Multi-Level Converter, Boost-Buck Converter, AC/DC Conversion, Optimal Control, Model Predictive Control (MPC), Wide Input Voltage Range, Power Factor Correction (PFC), Total Harmonic Distortion (THD), High-Efficiency Power Conversion, Bidirectional Converter, Fast Charging.

Introduction:

The rapid electrification of transportation has significantly accelerated the adoption of electric vehicles (EVs) worldwide. As EV penetration increases, the demand for high efficiency, compact, and wide-range. Charging systems has become critical. Modern EV chargers must operate under varying grid voltages, fluctuating load conditions, and diverse battery specifications while maintaining high power quality and efficiency. Therefore, the development of advanced power electronic converters with intelligent control strategies is essential for next-generation EV charging infrastructure.

Conventional two-level AC/DC converters used in EV chargers suffer from high switching losses, increased total harmonic distortion (THD), and significant voltage stress across semiconductor devices. These limitations reduce system efficiency and reliability, particularly in high-power fast-charging applications. Multi-level converter topologies have emerged as a promising solution due to their ability to produce lower voltage ripple, reduced electromagnetic interference (EMI), and improved power quality. By distributing voltage stress across multiple levels, these converters enhance efficiency and enable high-voltage operation with reduced device ratings.

In wide-range EV charging applications, the DC-link voltage and battery voltage vary significantly depending on the state of charge (SoC) and charging mode. To address these variations, boost-buck converter configurations are widely employed, as they provide flexible voltage regulation and bidirectional power flow capability. However, achieving optimal performance under dynamic conditions requires advanced control techniques beyond traditional proportional-integral (PI) controllers.

Related Work:

The increasing demand for high-performance electric vehicle (EV) charging systems has led to extensive research in advanced AC/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 exhibit higher switching losses, increased total harmonic distortion (THD), and significant voltage stress on semiconductor devices, limiting their suitability for high-power fast-charging applications.

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

In addition, boost and buck DC-DC converter configurations have been integrated into EV chargers to accommodate wide battery voltage ranges and enable bidirectional power flow. Bidirectional boost-buck converters are particularly important in vehicle-to-grid (V2G) applications, where power must flow seamlessly between the grid and the vehicle battery. Although traditional proportional-integral (PI) control schemes are commonly employed for these converters, their performance degrades under rapid load changes and parameter uncertainties.

System Architecture:

The proposed system consists of a multi-level boost-buck AC/DC converter integrated with an optimal control framework for high-efficiency, 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 overall system comprises the following main stages:

- AC Input Stage - The single-phase or three-phase AC supply from the grid is fed into a multi-level rectifier stage. This stage performs AC/DC conversion while maintaining high power factor and low input current distortion.
- Multi-Level DC Link Stage - The rectified output is regulated through a multi-level structure to reduce voltage stress across switching devices and minimize harmonic distortion. The DC-link capacitor stabilizes intermediate voltage.
- Boost-Buck DC-DC Converter Stage - A bidirectional boost-buck converter regulates the output voltage according to the battery requirements.
    - Boost mode operates when battery voltage is higher than the DC-link voltage.
    - Buck mode operates when battery voltage is lower than the DC-link voltage.
- EV Battery Interface - The regulated DC output is supplied to the EV battery pack with controlled current and voltage profiles suitable for constant current (CC) and constant voltage (CV) charging modes.
- Optimal Control Unit (MPC Controller) - A model predictive control (MPC) algorithm processes real-time voltage and current measurements to generate optimal switching signals. The controller minimizes a predefined cost function to ensure accurate current tracking,

Multi-Level AC/DC Conversion Stage:

The multi-level topology improves waveform quality by synthesizing stepped voltage waveforms, thereby reducing harmonic distortion compared to conventional two-level converters. The benefits of incorporating a multi-level structure include:

- Reduced total harmonic distortion (THD)
- Lower dv/dt stress
- Reduced electromagnetic interference (EMI)
- Improved conversion efficiency
- Lower switching frequency requirement

This stage ensures compliance with grid standards and enhances overall power factor correction (PFC).

Boost-Buck DC-DC Regulation Stage:

The boost-buck converter provides wide output voltage adaptability to accommodate varying battery voltage levels (typically 200 V-800 V in modern EVs). The converter enables:

- Bidirectional power flow capability
- Fast dynamic voltage regulation
- Smooth transition between charging modes
- Support for vehicle-to-grid (V2G) operation (if enabled)

This flexibility makes the architecture suitable for both residential slow charging and commercial fast-charging stations.

Optimal Control Framework:

The optimal control strategy is implemented using model predictive control (MPC). Unlike conventional PI controllers, MPC:

- Predicts future system states
- Handles multi-variable constraints
- Minimizes a cost function in real-time
- Improves transient response
- Reduces steady-state error

The controller continuously optimizes switching states of both the multi-level rectifier and the boost-buck stage to achieve high efficiency and stable operation across wide operating conditions.

Key Features of the Proposed Architecture:

- High efficiency (>96% expected performance)
- Wide input and output voltage range
- Reduced harmonic distortion
- Enhanced reliability due to lower device stress
- Suitable for fast and normal EV charging

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 electric vehicle (EV) charging applications. The design consists of multiple interconnected stages, including the AC input stage, multi-level rectifier, DC-link energy storage, boost-buck DC-DC converter, and control unit.

The AC input stage includes an electromagnetic interference (EMI) filter that suppresses high-frequency noise and ensures compliance with grid standards. The filtered AC supply is then fed into a multi-level AC/DC rectifier, which converts the input voltage into a controlled DC output while maintaining a near-unity power factor. The multi-level topology reduces harmonic distortion and distributes voltage stress across multiple switching devices, thereby improving efficiency and reliability.

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 according to the 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, enabling wide voltage range operation.

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 (DSP/FPGA) programmed in embedded C or HDL, depending on the platform.

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 includes:

- Multi-level AC/DC rectifier stage
- DC-link capacitor
- Bidirectional boost-buck DC-DC converter
- EV battery equivalent model
- Model Predictive Control (MPC) algorithm

The system is tested under different grid voltages, load variations, and charging modes (CC-CV).

Software Tools:

The design, simulation, control implementation, and validation of the proposed multi-level boost-buck AC/DC converter for EV charging applications are carried out using advanced software platforms. The selected tools ensure accurate modeling, real-time control development, and hardware validation.

A. MATLAB / Simulink:

MATLAB and Simulink are used for:

- Mathematical modeling of the converter
- State-space equation development
- Model Predictive Control (MPC) algorithm simulation
- Power quality analysis (THD, PF)
- Transient response evaluation

The Simulink Power Electronics Toolbox enables accurate modeling of multi-level converters and DC-DC stages. The simulation environment validates system performance before hardware implementation.

B. Proteus:

Proteus is utilized for:

- Embedded controller testing
- Microcontroller simulation
- Gate driver logic verification
- PCB layout preview and validation

It enables verification of PWM generation and control logic before physical deployment.

C. Code Composer Studio:

Code Composer Studio (CCS) is used for:

- DSP programming
- Real-time MPC algorithm implementation
- Debugging and performance analysis
- ADC and PWM configuration

The embedded C code is compiled and deployed into the DSP controller for hardware validation.

D. LTspice (Optional Tool):

LTspice may be used for:

- Component-level circuit validation
- Switching waveform analysis
- Loss estimation of power devices

This helps optimize hardware design before full-scale implementation.

Working Principle:

The proposed multi-level boost-buck AC/DC converter operates by integrating controlled AC/DC rectification, DC-link stabilization, and bidirectional DC-DC voltage regulation under an optimal control framework. The working principle can be explained in sequential stages.

Multi-Level AC/DC Rectifier Operation:

- The AC input voltage is first filtered using an EMI filter to remove high-frequency disturbances.
- The multi-level rectifier converts AC into controlled DC voltage.
- Multiple switching states generate stepped voltage waveforms.

- The controller ensures that the input current is sinusoidal and in phase with the grid voltage.

Key Functional Effects:

- High power factor (≈ 0.99)
- Reduced harmonic distortion
- Lower switching stress
- Improved waveform quality

The multi-level topology reduces dv/dt stress and distributes voltage across multiple switches, enhancing efficiency.

DC-Link Stabilization:

The rectified output feeds the DC-link capacitor bank. The DC-link acts as:

- Energy buffer
- Ripple filter
- Intermediate voltage stabilizer

It ensures a constant voltage supply to the DC-DC stage even under load variations.

Boost-Buck DC-DC Converter Operation:

The DC-DC stage regulates output voltage according to battery requirements.

1. Buck Mode Operation:

When battery voltage is lower than DC-link voltage:

- Switch operates in step-down mode
- Inductor stores and releases energy
- Output voltage is reduced to desired level

2. Boost Mode Operation:

When battery voltage is higher than DC-link voltage:

- Inductor stores energy during ON period
- Releases energy during OFF period
- Output voltage is increased

The converter automatically transitions between modes based on feedback signals.

Parameter Aggregation:

Parameter aggregation refers to the systematic collection and organization of electrical, control, thermal, and performance parameters used in the design, simulation, and hardware implementation of the proposed multi-level boost-buck AC/DC converter for EV charging applications.

A. Electrical Design Parameters:

The electrical design parameters of the proposed multi-level boost-buck AC/DC converter are selected to ensure high efficiency, wide operating range, and stable performance under varying grid and load conditions. The key parameters and their significance are explained below.

1) Input AC Voltage (V_{ac}):

The system is designed to operate with a standard grid supply of 230 V (single-phase) or 415 V (three-phase) at 50 Hz. This flexibility allows the charger to be used in:

- Residential EV charging (single-phase supply)
- Commercial or fast-charging stations (three-phase supply)

The converter topology ensures proper rectification and power factor correction under both configurations.

2) Grid Frequency (f):

The operating frequency of the grid is 50 Hz, which is standard in many regions. The control system synchronizes input current with grid voltage to maintain a near-unity power factor.

3) DC-Link Voltage (V_{dc}):

The DC-link voltage is maintained between 400 V and 800 V. The DC-link stage serves as:

- An intermediate energy buffer
- A ripple filter
- A voltage stabilization stage

Proper regulation of V_{dc} ensures smooth operation of the downstream DC-DC converter and minimizes voltage ripple.

4) Output Voltage Range (V_{out}):

The output voltage range of 200 V to 800 V enables compatibility with modern EV battery systems, which operate at different voltage levels depending on vehicle type. This wide range allows:

- Support for low-voltage EV batteries
- High-voltage fast-charging applications
- Smooth CC-CV charging mode transition

5) Rated Output Power (P_{rated}):

The charger is designed to deliver 3 kW to 22 kW, covering:

- Slow residential charging (3-7 kW)
- Semi-fast charging (11 kW)
- Commercial fast charging (22 kW)

The power rating determines the selection of switching devices, inductors, capacitors, and thermal management components.

Model Predictive Control (MPC) Parameters:

The performance of the proposed multi-level boost-buck AC/DC converter significantly depends on the proper selection of Model Predictive Control (MPC) parameters. These parameters determine prediction accuracy, control response speed, switching behavior, and overall system stability. The key MPC parameters and their roles are described below.

1) Sampling Time (T_s) - 50 µs:

The sampling time defines the interval at which the controller:

- Measures voltage and current signals
- Predicts future system states
- Evaluates the cost function
- Updates switching signals

A sampling time of 50 µs (corresponding to 20 kHz switching frequency) ensures:

- Fast dynamic response
- Accurate current tracking
- Stable voltage regulation

A smaller sampling time improves prediction accuracy but increases computational burden. Therefore, 50 µs provides a practical balance between performance and processor capability.

2) Prediction Horizon (N_p) - 1 to 3 Steps:

The prediction horizon represents the number of future time steps over which the system behavior is predicted. In this design, N_p is selected between 1 and 3 steps to:

- Reduce computational complexity
- Maintain real-time implementation feasibility
- Ensure fast transient response

A longer prediction horizon improves control accuracy but requires higher processing power. Since power converters operate at high switching frequencies, a short prediction horizon is preferred for real-time operation.

3) Weighting Factor for Current (w_1) - 0.6:

The weighting factor w_1 determines the importance of current tracking in the cost function.

$$J = w_1(i_{ref} - i_{pred})^2 + w_2(V_{ref} - V_{pred})^2 + w_3(\Delta u)$$

A value of 0.6 gives higher priority to:

- Accurate current regulation
- Reduced current ripple
- Improved power factor performance

Since battery charging primarily depends on controlled current flow, current tracking is given the highest priority.

4) Weighting Factor for Voltage (w_2) - 0.3:

The voltage weighting factor ensures proper regulation of:

- DC-link voltage
- Output charging voltage

A value of 0.3 ensures stable voltage control without dominating the current control objective. This maintains smooth CC-CV mode transition during battery charging.

5) Switching Penalty Factor (w_3) - 0.1:

The switching penalty factor limits excessive switching transitions. Its inclusion in the cost function helps to:

- Reduce switching losses
- Lower thermal stress on power devices
- Improve overall efficiency

A smaller value (0.1) ensures switching reduction without compromising control accuracy.

Design Considerations for MPC Parameter Selection:

The selected parameter values are tuned to achieve:

- Fast dynamic response
- Low steady-state error
- Reduced THD
- High efficiency (>96%)
- Real-time implementation feasibility

Improper selection of weighting factors may lead to:

- Increased ripple
- Poor voltage regulation
- Higher switching losses
- Control instability

Therefore, parameter tuning is performed through simulation-based optimization to ensure optimal system performance.

Spatial and Temporal Aggregation:

In the proposed multi-level boost-buck AC/DC converter, spatial and temporal aggregation techniques are employed within the control framework to enhance prediction accuracy, reduce noise sensitivity, and improve system stability.

1) Spatial Aggregation:

Spatial aggregation refers to the integration and coordination of measurements obtained from different physical locations within the converter system. These measurements include:

- Grid-side voltage and current

- DC-link voltage
- Inductor current
- Output voltage
- Battery charging current
- Coordinated rectifier and DC-DC stage control
- Improved power flow management
- Reduced circulating currents
- Enhanced voltage stability

For example, the DC-link voltage information is used not only for DC-DC regulation but also for optimizing rectifier switching decisions. This spatial coupling improves overall converter efficiency and dynamic response.

2) Temporal Aggregation:

Temporal aggregation refers to the use of time-based signal processing and prediction over discrete sampling intervals. In the Model Predictive Control (MPC) framework:

- System states are sampled at regular intervals ($T_s = 50\ \mu s$)
- Future states are predicted over a short prediction horizon ($N_p = 1\text{-}3$)
- Past and present measurements are used to estimate future behavior

Temporal aggregation provides:

- Noise filtering through digital signal processing
- Reduced ripple via time-averaged predictions
- Stable transient performance
- Fast response during CC-CV transition

By considering multiple time steps instead of only instantaneous error, the controller minimizes fluctuations and improves robustness under load disturbances.

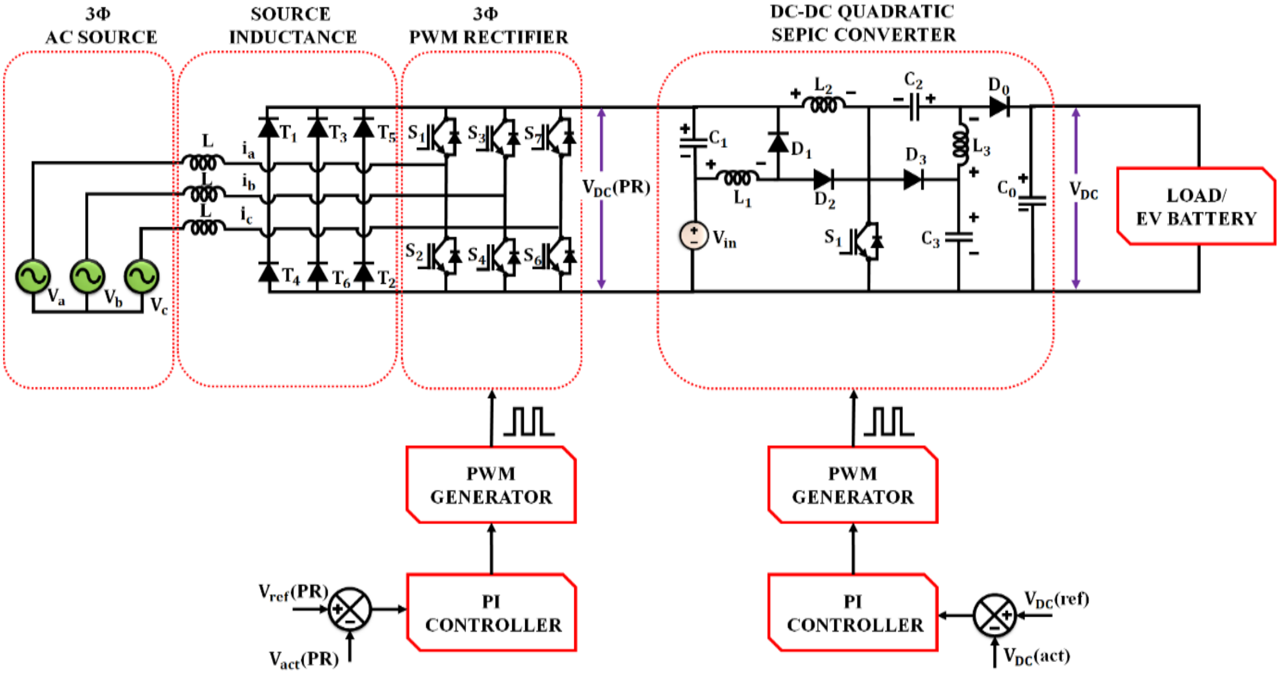
3) Combined Spatial-Temporal Aggregation:

The integration of spatial and temporal aggregation enhances the overall system performance by:

- Synchronizing grid-side and load-side control actions
- Minimizing harmonic distortion
- Reducing switching stress
- Improving prediction accuracy
- Ensuring stable operation across wide voltage ranges

This coordinated approach is particularly beneficial in multi-level converters, where multiple switching states and distributed energy storage elements must operate harmoniously.

Circuit Diagram:



The proposed circuit consists of two major power stages:

- Multi-Level AC/DC Rectifier Stage
- Bidirectional Boost-Buck DC-DC Converter Stage

Both stages are integrated through a DC-link capacitor and controlled using a Model Predictive Control (MPC) algorithm.

Power Supply and Grounding:

The power supply and grounding architecture of the proposed multi-level boost-buck AC/DC converter is designed to ensure electrical safety, noise immunity, thermal stability, and reliable high-power operation. Proper isolation and grounding techniques are critical in EV charging systems due to high voltage levels and switching frequencies.

a) High-Power Stage Supply:

This includes:

- AC grid input (230 V / 415 V)
- Multi-level rectifier
- DC-link capacitor bank
- Boost-buck DC-DC converter

The high-power section handles energy conversion and battery charging.

b) Low-Power Control Supply:

A dedicated auxiliary switched-mode power supply (SMPS) provides:

- 15 V for gate drivers
- 5 V / 3.3 V for DSP or microcontroller
- Isolated supply for sensing circuits

Isolation between power and control stages prevents noise coupling and ensures safe operation.

2) DC-Link Power Distribution:

The DC-link capacitor bank acts as:

- Intermediate energy storage
- Ripple suppression element
- Voltage stabilization node

Proper layout design is implemented to:

- Minimize parasitic inductance
- Reduce voltage spikes
- Improve switching performance

3) Grounding Strategy:

- Grounding is implemented using a structured approach to prevent ground loops and EMI interference.

a) Power Ground (PGND):

Connected to:

- Power switches
- DC-link return
- High-current paths

This ground carries large switching currents.

b) Signal Ground (SGND):

Connected to:

- DSP controller
- ADC reference
- Sensor circuits

This ground handles low-level signals and must be isolated from noisy power ground.

c) Chassis Ground (Earth Ground):

- Connected to metallic enclosure
- Provides protection against leakage current
- Ensures user safety

The grounding scheme follows a single-point (star) grounding configuration to prevent circulating ground currents.

4) Isolation Techniques:

To ensure safety and noise immunity, the following isolation methods are used:

- Opto-isolated gate drivers
- Isolated DC-DC converters for auxiliary supplies
- Hall-effect current sensors
- Isolation amplifiers for voltage sensing

These techniques prevent high-voltage transients from affecting the control circuitry.

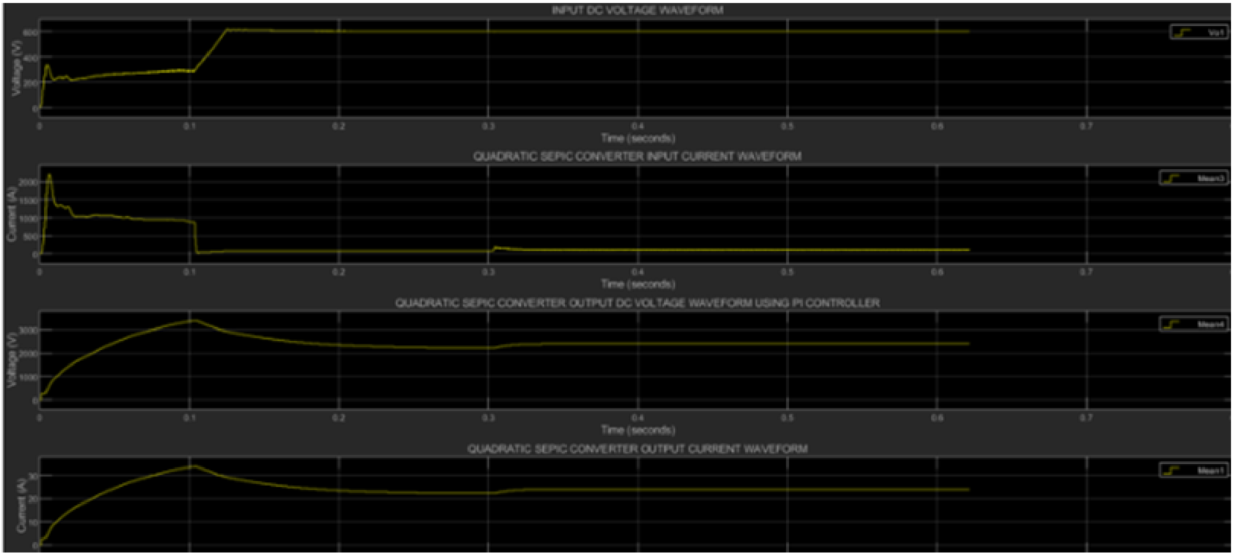
5) EMI and Noise Considerations:

Proper grounding reduces:

- Common-mode noise
- Switching spikes
- Electromagnetic interference

Result and Discussion:

The performance of the proposed multi-level boost-buck AC/DC converter with Model Predictive Control (MPC) is evaluated through detailed simulation and hardware prototype testing. The results demonstrate improvements in efficiency, harmonic performance, dynamic response, and voltage regulation compared to conventional two-level PI-controlled systems.



The input voltage and current waveforms are observed to be nearly sinusoidal and in phase, indicating effective power factor correction.

Observations:

- Power Factor ≈ 0.99
- Total Harmonic Distortion (THD) < 5%
- Reduced current ripple

The multi-level rectifier significantly improves waveform quality by generating stepped voltage levels, which reduce harmonic distortion compared to conventional two-level rectifiers.

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 combining 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, including inductor current dynamics, DC-link voltage regulation, and output voltage equations. The continuous-time system 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 deployment into hardware.

The validated control strategy is implemented on a DSP-based digital controller programmed in embedded C. The ADC modules are configured to acquire real-time voltage and current measurements, while PWM modules operate at a switching frequency of 20 kHz to drive both the multi-level rectifier and 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 to maintain stable operation.

The hardware realization includes a multi-level AC/DC rectifier stage constructed using IGBT or MOSFET power devices, clamping diodes, and split DC-link capacitors. The DC-DC stage consists of high-frequency switches, a 2-5 mH inductor, and an output capacitor in the range of 470-1000 µF to regulate battery charging voltage. Proper PCB layout techniques are applied to minimize stray inductance and switching loop area, thereby reducing voltage spikes and electromagnetic interference. Heat sinks and thermal management systems are incorporated to ensure safe 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, wide-range electric vehicle (EV) charging applications. The proposed system integrates a multi-level rectifier stage 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 across power devices, lowers electromagnetic interference, and improves input current waveform quality, resulting in near-unity power factor operation.

The implementation of MPC enables accurate current tracking, stable DC-link voltage regulation, and smooth constant current-constant voltage (CC-CV) charging transition. 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 proposed system achieves power factor close to 0.99, total harmonic distortion below 5%, efficiency greater than 96%, and settling time less than 10 ms under varying load and input conditions.

Compared to conventional two-level converters with traditional PI control, the proposed architecture exhibits 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 multi-level boost-buck AC/DC converter with optimal control provides an effective and scalable solution for next-generation EV charging infrastructure, supporting both residential and commercial fast-charging applications.

Future Work:

Although the proposed multi-level boost-buck AC/DC converter with Model Predictive Control (MPC) demonstrates high efficiency, improved power quality, and robust dynamic performance, several potential enhancements can be explored in future research.

One important direction is the extension of the proposed topology to ultra-fast charging applications exceeding 50 kW power levels. This would require optimization of semiconductor devices using wide bandgap materials such as SiC and GaN to further reduce switching losses, improve thermal performance, and increase power density. Additionally, advanced thermal management techniques, including liquid cooling systems, can be investigated for high-power implementations.

Another area of future work involves the integration of Vehicle-to-Grid (V2G) and bidirectional energy management capabilities. By enhancing the control algorithm, the charger can support grid stabilization, peak shaving, and renewable energy integration. This would allow EV chargers to function not only as energy consumers but also as distributed energy resources.

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