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Innovative Model Predictive Control of a Bidirectional DC–DC Converter for Enhanced Solar-Powered Electric Vehicle Charging

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KEYWORDS

Bidirectional DC–DC Converter, Model Predictive Control, EV Charging, VehicletoGrid, Solar Photovoltaic, Smart Grid

ABSTRACT

The increasing adoption of electric vehicles (EVs) and the expansion of distributed renewable energy sources have created a strong demand for advanced, adaptable, and intelligent charging infrastructure. Bidirectional DC–DC converters are key components that enable seamless power exchange between the grid and vehicles, supporting both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operations and facilitating integration with smart grids. This study introduces a model predictive control (MPC) approach for a bidirectional buck–boost DC–DC converter designed for solar-assisted EV charging stations. The controller optimizes the converter's switching actions in real time, reducing deviations in current and voltage while adhering to operational constraints. A discrete-time mathematical model of the converter is developed to define the control objectives. Simulations are carried out in MATLAB/Simulink across various scenarios, including transitions between G2V and V2G modes. The results indicate that the MPC controller achieves faster transient responses, lower overshoot, and improved energy efficiency relative to conventional PI control methods. Additionally, it enhances power stability and quality under fluctuations in renewable energy supply. Overall, the proposed MPC-based scheme provides a robust and scalable control framework for next-generation EV charging systems integrated with solar PV and energy storage solutions.

I. INTRODUCTION

The accelerating global transition toward cleaner mobility has made electric vehicles (EVs) a key element of the emerging green economy. However, the growing penetration of EVs places considerable strain on existing power systems, especially in terms of peak load handling and grid stability. To address these concerns, integrating distributed renewable energy sources articularly solar photovoltaic (PV) systems into EV charging infrastructure has become increasingly important. In this context, bidirectional DC–DC converters play a vital role by enabling both Grid-to-Vehicle (G2V) charging and Vehicle-to-Grid (V2G) operation. This dual functionality allows EVs to serve as mobile energy storage units that can supply power back to the grid during high-demand periods, thereby improving grid reliability, lowering operational costs, and enhancing the effective use of intermittent renewable energy.

Recent studies present a wide range of control techniques aimed at improving the performance of such power electronic systems. Various converter configurations have been investigated, including multilevel converters that offer improved fault tolerance [1-2] and active clamp forward converters designed for high-efficiency power conversion [7]. Although conventional controllers like proportional-integral (PI) and fuzzy logic methods are commonly employed in fast charging applications, they often exhibit limitations when dealing with system nonlinearities and fast dynamic responses required in modern smart grids [6]. As a result, there is a noticeable shift toward more advanced control approaches. Model Predictive Control (MPC), in particular, has gained attention for its capability to manage bidirectional power flow while accommodating multiple system constraints [3-5]. More recent developments have further explored adaptive and robust predictive current control techniques to ensure stable operation of distributed energy storage systems, even under the variable nature of solar PV generation [8].

This work aims to develop and implement an MPC-based control strategy for a bidirectional buck-boost DC–DC converter intended for solar-assisted EV charging stations. A discrete-time mathematical model of the converter is formulated to enable real-time optimization of switching actions, minimizing errors in voltage and current tracking. Unlike traditional control schemes, the proposed MPC framework explicitly incorporates system constraints and facilitates smooth transitions between G2V and V2G modes. Simulation studies carried out in MATLAB/Simulink demonstrate that the MPC-based approach achieves improved transient performance, reduced overshoot, and better power quality compared to conventional PI control methods, making it a promising and scalable solution for future smart energy systems.

Section II explains the system's working mechanism and introduces the small-signal modeling of the DC–DC converter. Section III describes the controller design methodology along with the key challenges involved. Section IV illustrates the simulation outcomes of the converter under PI control. Finally, Section V presents the concluding remarks, validating the performance and effectiveness of the proposed controller.

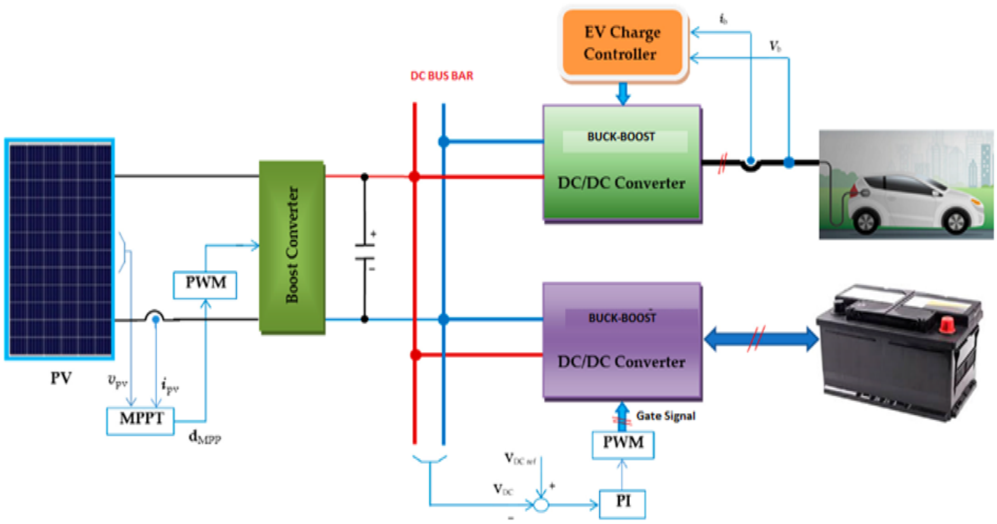

Fig.1. Solar Integrated Off Board Charging Unit

2. ANALYSIS OF CONVERTER

The off-board charging station simulation is developed in MATLAB, as depicted in Figure 1. A three-phase voltage source, paired with a star/delta transformer, is utilized to adjust voltage and current levels on the AC side. To achieve AC-DC conversion, a three-phase, three-level bridge converter is employed. A DC regulator generates the control signals necessary to manage active and reactive power at the grid interface. This bridge converter provides a high-voltage, low-current DC input to the DC-DC converter, which is then used to regulate output and supply the charging unit with the desired current or voltage range. Consequently, a Fly back step-down converter, shown in Figure 2, is implemented.

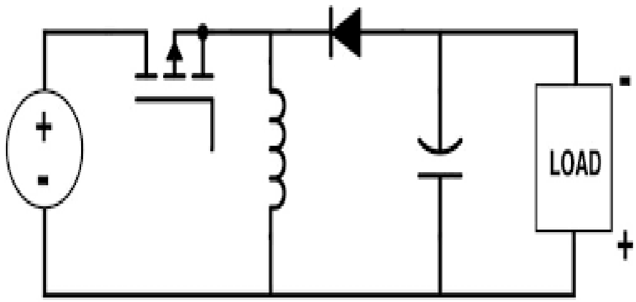

Fig.2. Buck-Boost Converter

This setup requires a controller to account for variations in the input supply and system parameters, necessitating a mathematical model for its design. The following sections outline the working principle and mathematical model of the converter. Figure 3 provides waveform illustrations to observe the converter's behavior.

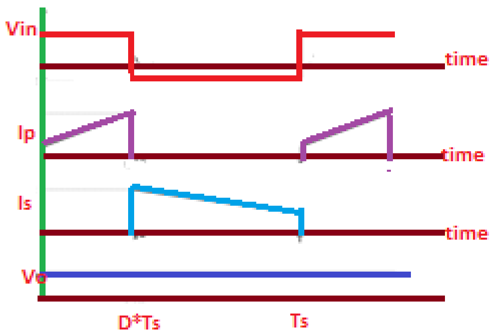

Fig.3. Buck-Boost Converter dynamics at CCM

The relation between input & output Voltage is,

$$\frac{V_0}{V_{in}} = \frac{D}{1-D} \qquad (1)$$

The isolated fly back converter operates in two main states within each switching cycle:

a) On-State (MOSFET ON): During this state, the input voltage is applied to the transformer's primary winding, causing energy to accumulate in the magnetic field of the transformer core. No energy is delivered to the output at this stage shown in Figure. 4.

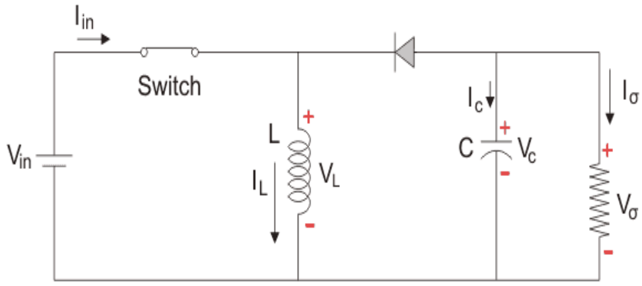

Fig. 4. Converter during T_{on}

b) Off-State (MOSFET OFF): In this state, the energy stored in the transformer core during the on-state is released to the secondary winding. It flows through a diode to supply power to the load and charge the output capacitor, depicted in figure.5.

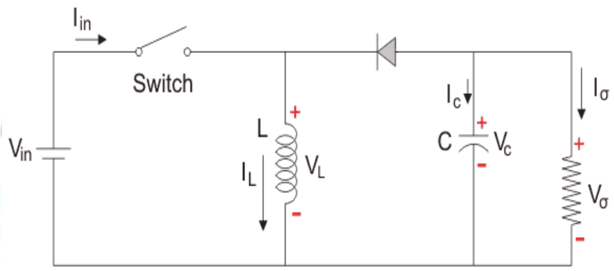

Fig. 5 Converter during T_{off}

Since there are two modes in Continuous Conduction Mode (CCM), equations for primary current, secondary current, and output voltage are derived for both the ON and OFF states of the main switch, corresponding to the equivalent circuits in Fig.4 and Fig.5. These equations are expressed in matrix form to obtain the state model, as shown in equations (2) and (3).

$$\begin{bmatrix} \frac{di_s}{dt} \\ \frac{dv_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_s \\ v_O \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{in} \qquad (2)$$

$$\begin{bmatrix} \frac{di_s}{dt} \\ \frac{dv_o}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ 0 & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_s \\ v_O \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{in} \qquad (3)$$

Equations (2) and (3) are averaged over one switching period to derive the state model, with the resulting model shown in equation (4)

$$A = \begin{bmatrix} 0 & -\frac{1-D}{L_s} \\ \frac{1-D}{C} & -\frac{1}{RC} \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \end{bmatrix}; C = \begin{bmatrix} 0 & 1 \end{bmatrix} \qquad (4)$$

The control to Output Transfer Function is given by

$$G(s) = \frac{\hat{V_0}(s)}{\hat{d}(s)} = \frac{V_{in}}{s^2 LC + s\frac{L}{R} + 1} \qquad (5)$$

After establishing mathematical model, the converter parameters are computed according to equations (6) to (9) using the considered system values and is provided in Table I.

Table I System Design Parameters

Parameter	Values with Units
Solar PV Modules	Sun Power SPR-305E, 15 modules, 4 strings
DC Bus Voltage	800V at 22.75A
Output Voltage of Converter	400V at 55A
Output Power	22KW
Converter Switching Frequency	100KHz
Battery Nominal Voltage	300V
Battery Capacity	12KWh
Battery State of Charge	50%
Inductance L	200 µH
Output Capacitor C	100 µF

$$V_{out} = \frac{D}{1-D} V_{in} = 400 \qquad (6)$$

$$L = \frac{V_0 D(1-D)}{f_s \Delta I_L} = 180\mu H \ \approx 200\mu H \qquad (7)$$

$$C_o = \frac{I_o D}{f_{s*} \Delta V} = \frac{120*0.5}{100000*4} = 68.7\mu F \approx 100\mu F \qquad (8)$$

3. CONTROLLER DESIGN

Using the parameters listed in Table 1, these coefficients were then simulated in MATLAB. A cascaded control structure with an outer voltage loop and inner current loop is adopted for regulating the bidirectional converter. The PI controller parameters are derived using a frequency-based design approach by selecting an appropriate bandwidth relative to the switching frequency. Based on system parameters, the proportional and integral gains are tuned to achieve a fast and stable response while minimizing steady-state error. The resulting controller ensures reliable voltage regulation under varying load conditions and serves as a baseline for comparison with advanced control strategies such as MPC. A systematic procedure is followed to design a conventional controller for the bidirectional converter. Initially, a small-signal model is derived to capture the system dynamics. A cascaded control structure with voltage and current loops is then implemented using PI controllers. The controller parameters are obtained based on frequency-domain considerations and further refined through simulation. The designed controller ensures stable operation and satisfactory transient performance, serving as a reference for comparison with advanced control techniques.

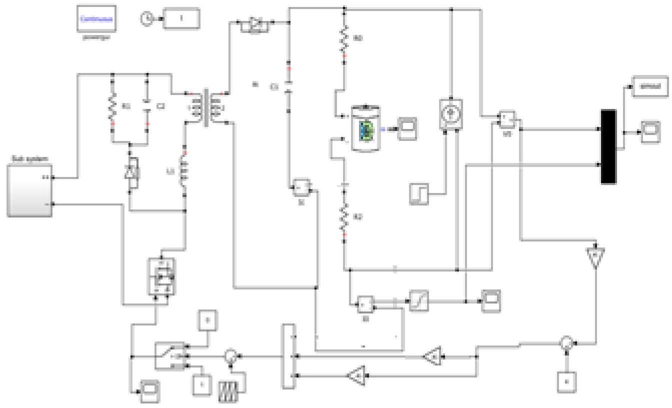

Fig.7. Simulation diagram of the system with SMC

4. SIMULATION RESULTS

Figures and Tables

The controller design process begins with defining system requirements, followed by developing a mathematical model and deriving the corresponding transfer function. A cascaded control structure is then selected, and a PI controller is employed. Initial controller gains are calculated based on design specifications and refined through simulation. The controller is validated under varying operating conditions to ensure stable and reliable performance. The system was evaluated through simulation using the chosen design parameters, which initially revealed a reduced phase margin along with a significant steady-state error. To overcome these limitations and achieve stable operation, a customized controller was designed. Figures 8 and 9 present the reference signals used for PWM generation in a three-level converter via a DC regulator. The inverter output, producing approximately 800 V at 60 A, is shown in Figure 8.

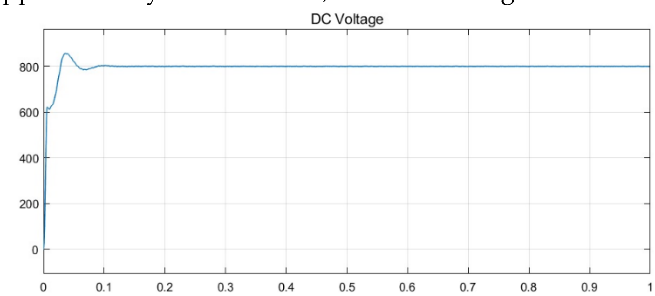

Fig.8 DC Bus Voltage

The controller-generated PWM pulses applied to the DC–DC converter are illustrated in Figure 9, while Figure 10 shows the converter output voltage regulated to the target value of 400 V.

During the charging operation, Figure 11 indicates a charging voltage of 340 V, which is higher than the nominal battery voltage of 320 V. To enable rapid charging, a constant current of 120 A is maintained throughout the process, as depicted in Figure 12. The results demonstrate that the system maintains accurate steady-state tracking even when a load disturbance is introduced at 0.005 seconds. The battery charging process proceeds with stable voltage and current levels, as evidenced by the state of charge (SOC) curve shown in Figure 13. Overall, these observations confirm the effectiveness of the converter design and its dependable performance under dynamic conditions

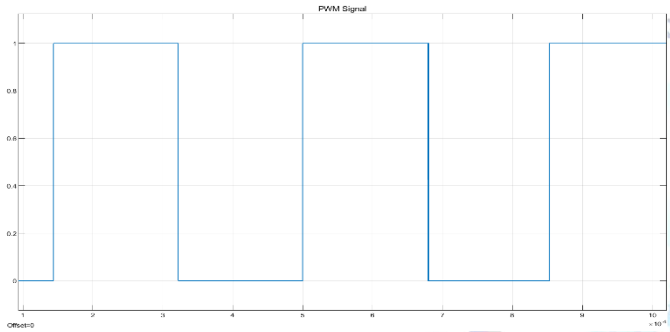

Fig.9.PWM signal to the DC-DC Converter

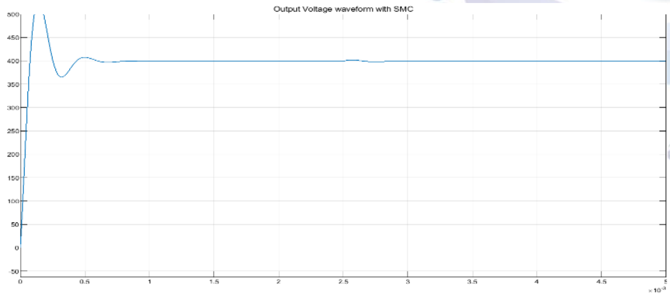

Fig.10 DC-DC Converter Output Voltage

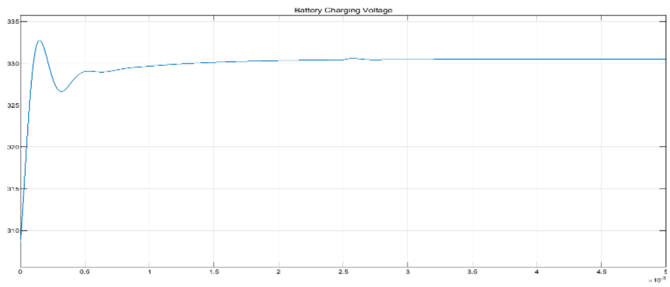

Fig.11 Battery Charging Voltage

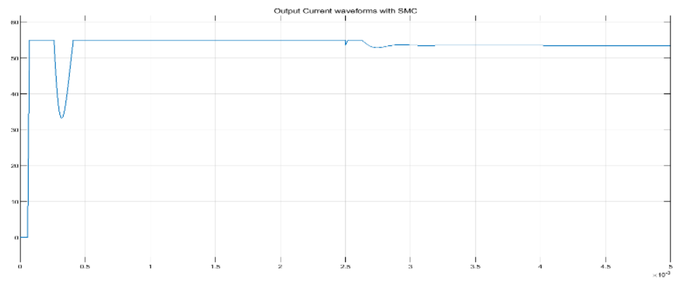

Fig.12. Charging Current of Battery

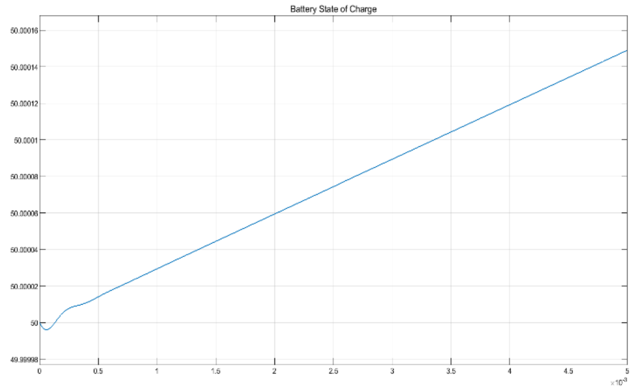

Fig.13. Battery State of Charge

5. CONCLUSION

This study effectively developed and verified a Model Predictive Control (MPC) strategy for a bidirectional buck–boost DC–DC converter operating in a solar-supported EV charging system. Using a discrete-time model, the controller was able to handle the intricate behavior of bidirectional power transfer and ensured smooth switching between Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes. The inclusion of solar PV and energy storage demonstrated improved stability under the MPC approach, as it dynamically regulated switching actions to accommodate fluctuations in renewable energy output. Simulation analysis carried out in MATLAB/Simulink indicates that the MPC-controlled converter delivers superior performance compared to traditional PI-based methods. The system exhibited quicker dynamic response and reduced overshoot under sudden load variations and operating mode transitions. Additionally, by maintaining operation within defined system constraints, the controller enhanced efficiency and power quality. Overall, the results highlight that the proposed MPC framework offers a reliable and scalable approach for future smart grid systems, enabling electric vehicles to function as active and dependable components in modern energy networks.

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Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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