



A COMPARISON OF PI AND MPC CONTROL STRATEGIES FOR BIDIRECTIONAL DC-DC CONVERTERS IN BATTERY SYSTEMS

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ABSTRACT

Currently, advances in research on battery energy storage systems (BESS), as well as their implementation in various renewable energy generation systems—environmentally friendly and based on non-storable primary resources such as wind and solar energy—have created a demand for highly functional DC–DC converters with diverse topologies, configurations, and bidirectional capabilities. This paper presents a comparison between a Proportional–Integral (PI) controller and a Model Predictive Control (MPC) strategy applied to a bidirectional DC–DC converter, focusing on the response times and dynamic behavior of both controllers. The DC–DC converter is connected to a BESS through the direct current link (DC link), and the main objective of both controllers is to regulate the DC link voltage to keep it within the required values. To achieve this, it is necessary to inject or absorb active power to charge or discharge the battery bank. The results validate the dynamic performance of the proposed controllers and highlight the differences in their transient responses.

Keywords: Bidirectional DC-DC, Battery Applications, PI and Model Predictive Controllers.

1 INTRODUCTION

The world is facing a variety of emerging environmental problems. In response to the search for sustainable alternatives, the generation of renewable energy has evolved, alleviating the burden on traditional energy sources (Hernandez et al., 2016). However, since renewable sources are intermittent and cannot be stored, energy storage systems (BESS) are necessary to maximize their use. These systems store energy during periods of excess generation and release it when demand exceeds supply. This improves the efficiency and stability of electrical systems, as demonstrated in (Pirooz; Noroozian, 2016) and (Tricarico et al., 2021).

Battery energy storage systems (BESS) have emerged as a key technological solution, driven by the energy transition and the commitment to reducing carbon dioxide emissions for environmental reasons. This shift has resulted in a substantial increase in renewable energy in many countries. According to the International Energy Agency (IEA), the global capacity of installed BESS was approximately 28 gigawatts (GW) in 2024 and is projected to exceed 600 GW by 2030, (“Global installed grid-scale battery storage capacity in the Net Zero Scenario, 2015-2030 – Charts – Data & Statistics”, [S.d.]). The implementation of these technologies is mainly driven by public policies, reduced costs of lithium-ion storage systems, and growing electrification of energy systems.

In this context, bidirectional DC-DC converters—also known as buck-boost converters—are essential for managing energy transfer between batteries and the power grid. These converters enable bidirectional energy flow, allowing flexible energy storage



and delivery (Sun; Cheng, 2020). However, controlling such converters poses a significant challenge due to the need for fast response in both charge and discharge modes (Zad et al., 2024).

In the case under study, cascade control is implemented with an outer loop regulating the voltage and an inner loop regulating the current. The inner loop typically exhibits a faster dynamic response (Augusto; Filho, [S.d.]; Pirooz; Noroozian, 2016; Zad et al., 2024). In the first case, a proportional–integral (PI) cascade controller is applied. However, this controller can experience significant delays when responding to dynamic changes because it does not predict the system’s future behavior. In the second case, a PI controller is used for the outer voltage loop, while model predictive control (MPC) is employed for the inner current loop. The inner controller is designed based on a model of the intended application and enables prediction of the system’s future behavior (Sun; Cheng, 2020; Vimala; Lokeshgupta; Naresh Kumar, 2025).

This comparison is motivated by the need to evaluate the dynamic response and robustness of controllers in the face of instantaneous changes in system variables. This analysis provides relevant information for selecting control strategies in BESS applications, especially when managing fluctuating renewable energies.

The developed control models are validated using the MATLAB/Simulink® computational tool. This article is structured as follows: Section II describes the design methodology used for the control cases under study. Section III presents the analysis and results. Finally, Section IV presents the most relevant conclusions and future work.

2 METHODOLOGY

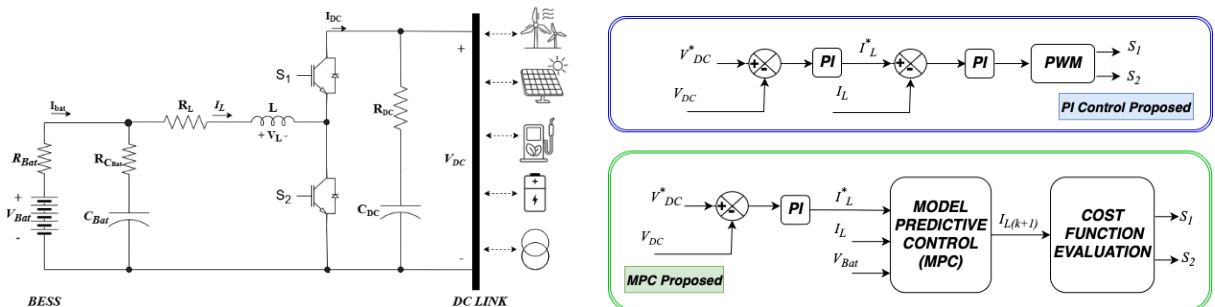
2.1. System configuration and mathematical modeling

The present work adopts the topology of a bidirectional converter, as shown in Figure 1, where the input is a BESS and the output is a DC link that can be interconnected with various power generation, energy supply, or storage systems. When S1 switches while S2 remains off, the converter operates in buck mode, allowing energy to flow from the DC link to the BESS for charging (Pirooz; Noroozian, 2016).

Conversely, when S2 switches while S1 remains off, the converter operates in boost mode, transferring energy stored in the BESS to the DC link and thereby discharging the storage system (Pirooz; Noroozian, 2016).

$$i_L(k+1) = \begin{cases} \frac{1}{L} \cdot [V_{Bat} - (i_L \cdot R_L)] & \text{Buck} \\ \frac{1}{L} \cdot [V_{Bat} - (i_L \cdot R_L) - V_{DC}] & \text{Boost} \end{cases} \quad (1)$$

Figure 1 - Control circuit and strategies of control to be used.





This behavior is detailed in equation 1 which describes the dynamic modeling of the topology shown in Figure 1.

2.2. PI Controller Modeling

The PI controller is widely used in converter design due to its simplicity and ease of implementation. As a linearized system, it has lower computational costs than predictive models. However, this also limits operation outside the linearization point, affecting the system's dynamic performance (Gil, 2016).

Designing the PI controller involves analyzing the frequency response of dynamic systems separately and considering the behavior of the transfer functions in buck and boost mode operations. First, this analysis is applied to the internal control loop (current), and then to the external control loop (voltage). The frequency domain analysis considers three main criteria:

- (i) The current loop's crossing frequency must be less than one-tenth of the transistor's switching frequency.
- (ii) The phase margin must be less than 180°.
- (iii) The internal loop must respond faster than the external loop (Gil et al., 2016).

Using Bode diagrams, we perform a frequency response analysis of the current control loop and found that the transfer function $G_i(s)$, presented in equation (2), is limited to a crossover frequency of F_c de 1.5 kHz and a phase margin of 59° when using the continuous-time control equation $C_i(s)$ presented in equation (3). This equation adjusts the system's natural frequency response to the desired value.

The Buck-Boost models are evaluated separately to obtain the following gains for the current loop: proportional $K_p = 16252$ and integral $K_i = 1625200$ for Buck mode, $K_p = 2.0405$ and $K_i = 11105.35$ for boost mode since the system is linearized using the small-signal model to deduce the transfer function, either pair of gains can allow the bidirectional converter to operate. For the case study, the gains obtained for boost mode are used because they provide a more stable response.

$$G_{(i)}(s) = \frac{\hat{i}_L}{\hat{d}} = \frac{V_{bat} \cdot (1 + R_{bat} \cdot C_{bat} \cdot s)}{C_{bat} \cdot L \cdot R_{bat} \cdot s^2 + L \cdot s + R_{bat}} \quad (2)$$

The terms in the above equation are defined as follows: C_{Bat} is the input capacitor, R_{Bat} is the internal resistance of the battery, and L is the inductance of the converter.

Since the analysis is carried out on a digital system, it is necessary to discretize this control function. For this purpose, the Tustin method (Gil et al., 2016) is used, thus obtaining the function $C_{di}(z)$ shown in equation (4).

$$C_i(s) = \frac{2.0405 \cdot (s + 5442.463)}{s} \quad (3) \quad C_{id}(z) = \frac{(2.087 \cdot z + 1.994)}{z - 1} \quad (4)$$

A frequency response analysis of the voltage control loop transfer function, $G_v(s)$, is performed, as shown in equation (5). Since the control system is implemented in a cascade configuration, is obtained the product of the capacitor voltage transfer function with respect to the inductor current, $G_{vi}(s)$, and the closed-loop current control function, $G_{i,c}(s)$.



$$G_v(s) = G_{vi}(s) \cdot G_{ic}(s) = \frac{d \cdot R_{DC}}{R_{DC} \cdot C_{DC} \cdot s + 1} \cdot G_{ic}(s) \quad (5)$$

The variables used in the above equation are defined as follows: d is the duty cycle; R_{DC} and C_{DC} are the resistance and capacitance of the DC link, respectively.

In accordance with the dynamic behavior of the system and in compliance with the established criteria, a crossover frequency F_c of 33.9 Hz is defined. This yields the voltage control function, $C_v(s)$ and its corresponding discrete expression, $C_{vd}(z)$.

$$G_v(s) = \frac{0.4081 \cdot s^2 \cdot 0.4081 \cdot s V_{bat} \cdot (1 + R_{bat} \cdot C_{bat} \cdot s)}{C_{bat} \cdot L \cdot R_{bat} \cdot s^2 + L \cdot s + R_{bat}} \quad (6)$$

$$C_v(s) = \frac{0.01073 \cdot (s + 1.631 \times 10^4)}{s} \quad (7)$$

$$C_{vd}(z) = \frac{(0.01146 \cdot z - 0.01)}{z - 1} \quad (8)$$

2.3. PI Control + Model Predictive Control (MPC)

Model Predictive Control (MPC) enables prediction of future plant states, which is advantageous for applications requiring rapid responses. This type of controller can optimize dynamic performance, manage system nonlinearities, and apply constraints directly, overcoming the limitations of other controllers. However, achieving these advantages requires high-quality plant modeling, leading to greater design complexity and significant computational effort. This indicates higher implementation costs and complexity (Cunha, 2020).

Based on the above description, two types of prediction models for buck and boost operations are analyzed (Sun; Cheng, 2020). Model predictive control (MPC) is generally classified into blocks of discrete-time modeling, prediction, and optimization processes. In this context, the external voltage control loop uses the same discrete-time PI controller strategy presented in (Augusto; Filho, [S.d.]) and as modeled in a previous section of this document. The internal current loop consequently, implements MPC, following the model formulation and cost function methodology described in (Tricarico et al., 2021) and (Vimala; Lokeshgupta; Naresh Kumar, 2025).

To obtain a discretized model derived from Equation 8, and using the *Forward Euler Method*, the discrete-time model of first-order systems can be obtained by approximating derivatives (Sun; Cheng, 2020). Equations 1 are used as prediction functions for the Buck and Boost operating modes, respectively.

$$i_L(k+1) = \begin{cases} \frac{T_s}{L} \cdot [V_{Bat}(k) \cdot S_1 - (i_L(k) \cdot R_L)] + i_L(k), & S_1 = [0,1] \text{ Buck} \\ \frac{T_s}{L} \cdot [V_{Bat}(k) - (i_L(k) \cdot R_L) - V_{DC}(k) \cdot (1 - S_2)], & S_2 = [0,1] \text{ Boost} \end{cases} \quad (9)$$

The MPC values define the output control actions depending on the variables in Buck and Boost modes, evaluated using the cost function (G), (Pirooz; Noroozian, 2016), during the sampling period T_s , it can be assumed that the reference current i_L^* remains constant (Sun; Cheng, 2020).

$$G_{Buck}(s) = |i_L^* - i_{L(k+1)Buck}| \quad (10)$$

$$G_{Boost}(s) = |i_L^* - i_{L(k+1)Boost}| \quad (11)$$



The current reference i_L^* is estimated from the voltage loop, and it is defined by:

$$i_L^* = (V_{DC}^* - V_{DC}) \cdot \left(K_p - \frac{K_i}{s} \right) \quad (12)$$

V_{DC} is the DC link voltage, V_{DC}^* is the reference voltage, K_p is the proportional gain, and K_i is the integral gain of the PI controller obtained for the first controller presented.

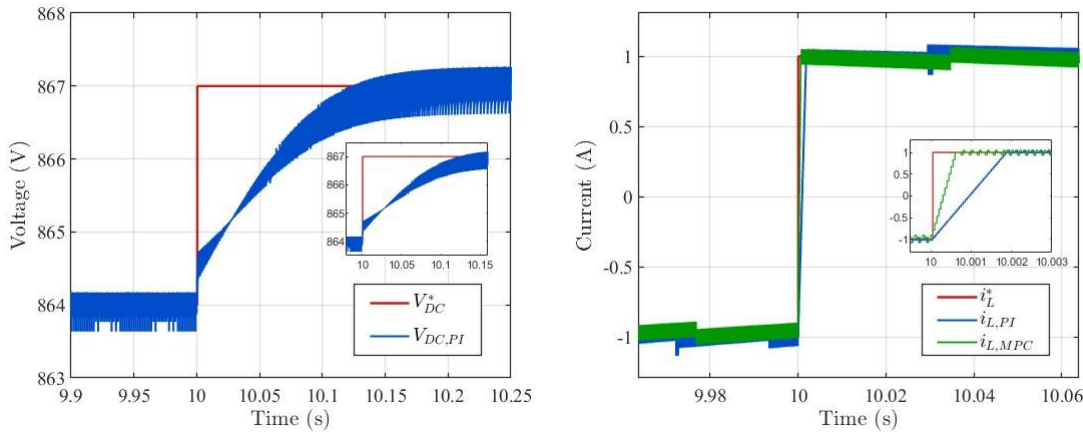
3 RESULTS AND DISCUSSION

To validate the converter's operation in the DC link, a battery with the same technology as the BESS battery is connected, but with different parameters such as voltage, current, and capacity. The selected batteries are made of lithium-ion material because it offers advantages such as robustness, capacity, and balance in terms of performance, environmental compatibility, and raw material availability (Asian Development Bank, 2018).

The DC-DC converter is designed with the following specifications: an input voltage of $V_{Bat} = 200 V$, an output voltage of $V_{DC} = 800 V$, an inductance of $L = 200 mH$, two capacitors of $C_{Bat} = 100 \mu F$ each, and a switching frequency of $F_s = 12 kHz$.

Figure 2a shows the voltage loop response and Figure 2b shows the current loop behavior for the different control types implemented with a sampling time of $T_s = 8,33 \mu s$. A voltage reference step from $V_{DC}^* = 864 V$ to $V_{DC}^* = 867 V$ was used to evaluate the buck and boost modes of operation, respectively.

Figure 2 - a. Voltage Control Response - b. Current Control Response.



To validate the operation of the current loop, it is initially evaluated in open loop for its two operating modes, where a unit step change in the reference current is injected from $i_L^* = -1 A$ to $i_L^* = 1 A$. A response time of $1,85 ms$ and a ripple of $162 mA$ in the current $i_{L,PI}$ (for the PI controller) are obtained, while for the MPC controller $i_{L,MPC}$ a response time of $0,7 ms$ and a ripple of $216 mA$ are obtained. This shows that the controlled signal regulating the inductor current via MPC has a faster response but a larger ripple compared to the response given by the PI controller.

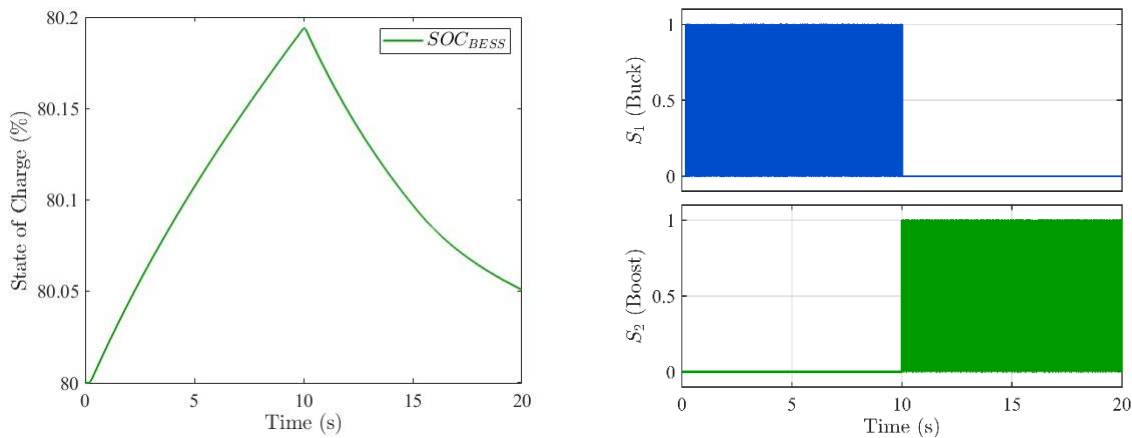


In Figure 2b, it can be observed that the voltage loop $V_{c,PI}$ presents a response time of 123 ms and a settling time of 200 ms along with a ripple of approximately 1 V in closed loop.

Figure 3a shows the state of charge (SOC) of the battery. In the first 10 seconds, the upward trend (in green) indicates that the battery energy storage system (BESS) is absorbing energy from the DC link. In the following 10 seconds, the downward trend indicates that the BESS is injecting energy into the DC link.

Figure 3b shows the steady-state operation of the converter in buck and boost modes, respectively. The transition between these two modes corresponds to the alternating mode, where switches S1 and S2 are alternately turned on and off.

Figure 3 - a. BESS and DC Link State of Charge b. Transition Two Operational Modes.



4 CONCLUSIONS

The topology used was chosen because it is expected to remain a key solution in energy storage systems for the next 30–40 years, due to its efficiency, reliability, and flexibility in managing energy flows between batteries and the grid.

This research applies two types of control strategies (PI and MPC) to a bidirectional DC–DC converter. Different activation modes are proposed for both control strategies in order to manage the charge and discharge modes of the BESS. However, it was observed that the MPC controller achieves a faster response than the PI controller, that is, it has better transient-state behavior, indicating a more robust controller but with greater implementation complexity. The complete simulation results show that the proposed strategies can be stabilized for each operating mode.

In future work, a comparison will be made with an MPC system that is also implemented in the voltage loop.

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