

Research Article

Voltage Regulation of Boost Converter Operating under Constant Power Load using Model Predictive Control

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ABSTRACT

In this study, the design of a Model Predictive Controller (MPC) is presented to regulate bus voltage and enhance the stability of a DC/DC boost converter in a DC microgrid operating under Constant Power Load (CPL). The primary objective of this study is to develop a nonlinear control technique capable of effectively stabilizing power converters in the presence of CPL, which has the potential to cause significant instability issues. When designing the proposed control approach, it is crucial to consider the nonlinear nature and negative impedance characteristics of CPL. The MPC controller aims to mitigate the instability problems caused by CPL directly connected to a DC/DC boost converter.

The proposed controller design ensures that the output voltage follows the predefined reference value, regardless of whether the system operates in continuous or discontinuous current mode. To demonstrate the effectiveness of the designed controller, comparative simulation studies have been conducted. In these simulations, performed using MATLAB/Simulink, the obtained results confirm that the DC bus voltage remains stable at the desired reference value. Furthermore, comparative simulation results were obtained and evaluated to compare the performance of MPC with a conventional PI controller. The simulation results indicate that MPC achieves significantly better tracking of the reference DC bus voltage compared to the conventional PI controller.

1. INTRODUCTION

The growing significance of renewable energy generation, particularly photovoltaics (PV) and energy storage modules, has increased interest in DC microgrids [1–3]. DC/DC boost converters are widely utilized as interface components in DC microgrids due to their capability to deliver a higher output voltage suitable for integration into standard systems [4,5].

The intrinsic non-minimum phase characteristic of boost converters presents challenges in controller design [6,7]. Compared to conventional PI controllers, nonlinear controllers exhibit superior dynamic performance and have the ability to accurately characterize the nonlinear behavior of converters [8]. Among the various existing control methods, the conventional sliding mode control approach employs an inductor current control scheme for boost converters, offering good robustness. However, this approach leads to complex control signal calculations and introduces the chattering problem [9,10].

On the other hand, fuzzy controllers demonstrate better representation capabilities for nonlinear systems and

effectively address the nonlinear model predictive (NMP) problem. However, increasing the number of fuzzy rules can enhance control performance while also introducing a heavier computational burden [11]. In recent years, model predictive control (MPC) has gained attention due to its fast response, explicit control constraints, and ease of implementation, making it an attractive choice for power converters [12]. Recent works have also examined its practical and experimental performance [13,14], its application in event-triggered strategies [15], and comparative studies with linear control methods in DC microgrids [16].

Various approaches have been proposed for DC/DC power electronic converters operating with CPLs. Passive damping techniques, including the addition of capacitors, resistors, or LC filters, are straightforward and effective; however, they can be costly and constrained by physical limitations. In contrast, active damping methods enhance system stability by adjusting control loops to mimic passive components like virtual capacitors, resistors, and impedances [17]. These active damping methods are equivalent to injecting stabilizing

power into the CPL, which may compromise load performance.

To prevent compromising load performance, a compensation method is proposed by modifying the control loop of the source converter to emulate a virtual resistor [18]. However, all these active damping methods rely on small-signal models and can only ensure stability within a limited range around the operating point. Consequently, they serve as local solutions, and when subjected to large disturbances, these linear control techniques lose effectiveness, potentially causing system instability [19]. Due to the nonlinear behavior of converters and the negative impedance characteristics of CPLs, nonlinear control strategies are crucial for maintaining system stability in a large-signal context.

MPC has attracted significant interest in the field of power converters and electric drives as an effective method for improving performance monitoring [20]. Another crucial factor that strongly affects the efficiency and stability of boost converters is the design of the switching frequency. Improper frequency selection may result in excessive switching losses, reduced lifetime of components, and increased electromagnetic interference (EMI). On the other hand, an optimized switching frequency ensures high efficiency, compact component sizing, and improved transient response [21,22]. Despite its importance, the systematic evaluation of switching frequency design has not been adequately addressed in the literature.

In this study, a comprehensive analysis of switching frequency selection in a boost converter is presented. The proposed approach combines MATLAB/Simulink simulations with performance evaluation to highlight the trade-offs between efficiency, voltage gain, and losses. The novelty of this work lies in emphasizing the role of switching frequency design as a critical parameter, which is often overlooked in nonlinear control-based studies.

The contributions of this article can be summarized as follows:

The effect of CPL load on converter performance, depending on switching frequency, is systematically investigated.

A simulation-based analysis is performed to evaluate efficiency, voltage gain, and loss distribution.

The results are interpreted, and the novelty of the proposed approach is highlighted by comparing it with a conventional PI controller.

The remainder of the article is organized as follows:

Section 2 presents the CPL and stability problem. Section 3 discusses the DC/DC boost converter with CPL load and voltage regulation using an MPC controller. Section 4 presents simulation results. Section 5 is the results and discussion section. The final section concludes the article with the main findings and future research directions.

2. CPL AND INSTABILITY PROBLEM

It is well known that a DC/DC converter with an ideally regulated output (i.e., tightly controlled) can exhibit unstable behavior when combined with an input filter (LC) [23]. This phenomenon was first examined in [24] by modeling a highly efficient power converter with ideal regulation through a CPL. To demonstrate the instability risk arising from the CPL problem, this section provides a detailed analysis.

Figure 1 illustrates the model of a high-efficiency converter in closed-loop operation combined with a second-order LC input filter. The resistor “ R_i ” represents losses. The state-space

equations of the system shown in Figure 1 can be expressed as follows.

$$\frac{di_L}{dt} = \frac{1}{L}(V_i - R_i i_L - v_C) \quad (1)$$

$$\frac{dv_C}{dt} = \frac{1}{C}\left(i_L - \frac{P_{CPL}}{v_C}\right) \quad (2)$$

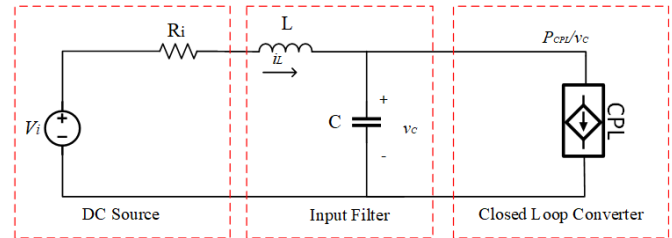


Figure 1. Model of a highly efficient converter with ideal regulation and an input filter.

The steady-state equilibrium point of the converter in Figure 1 is given by Equations (1) and (2).

$$i_L^* = \frac{P_{CPL}}{v_C^*} \quad (3)$$

$$v_C^* = \frac{V_i}{2} \mp \sqrt{\left(\frac{V_i}{2}\right)^2 - R_i P_{CPL}} \quad (4)$$

Looking at the formula in Equation (4), three possible cases arise:

Case 1: Two equilibrium points are formed, as shown in Equation (5).

$$\left(\frac{V_i}{2}\right)^2 > R_i P_{CPL} \quad (5)$$

Case 2: A single equilibrium point is formed, as shown in Equation (6).

$$\left(\frac{V_i}{2}\right)^2 = R_i P_{CPL} \quad (6)$$

Case 3: No equilibrium point is formed, as shown in Equation (7).

$$\left(\frac{V_i}{2}\right)^2 < R_i P_{CPL} \quad (7)$$

The three conditions mentioned above can be geometrically represented in the v_C, i_L plane, as shown in Figure 2, when the system is in equilibrium, based on Equations (1) and (2).

According to Equations (1) and (2), the equilibrium condition can be expressed as given in Equations (8) and (9).

$$v_C = V_i - R_i i_L \quad (8)$$

$$v_C i_L = P_{CPL} \quad (9)$$

Equations (8) and (9) are plotted in Figure 2 to show the conditions of Equations (5) and (6) for different R_i values. The equality in Equation (5) corresponds to Case 1, the equality in Equation (6) corresponds to Case 2, and the equality in Equation (7) corresponds to Case 3.

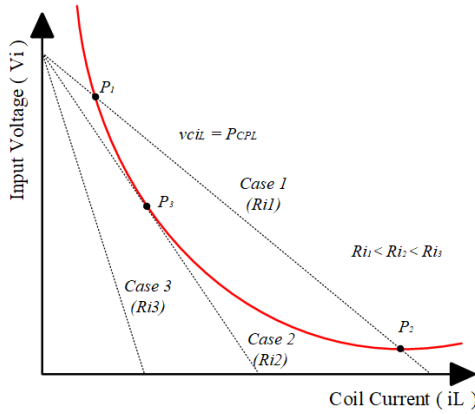


Figure 2. Intersection of the CPL characteristic curve with the load line.

Additionally, when determining the existence of the equilibrium point in Equations (1) and (2), the stability should also be considered. Let the DC source voltage and inductor current be defined as $v_C = V_C^* + \hat{v}_C$ and $i_L = I_L^* + \hat{i}_L$ respectively. Then, linearizing the equations (1) and (2) around the equilibrium point given by (3) and (4) will result in the following small-signal model.

$$\frac{d\hat{i}_L}{dt} = -\frac{R_i}{L}\hat{i}_L - \frac{1}{L}\hat{v}_C - \frac{1}{L}\hat{V}_i \quad (10)$$

$$\frac{d\hat{v}_C}{dt} = \frac{1}{C}\hat{i}_L + \frac{P_{CPL}}{CV_C^{*2}}\hat{v}_C \quad (11)$$

The characteristic equation corresponding to equations (10) and (11) is given as follows.

$$s^2 + s\left(\frac{R_i}{L} - \frac{P_{CPL}}{CV_C^{*2}}\right) + \frac{1}{LC} = 0 \quad (12)$$

Therefore, equations (10) and (11) small signal dynamics will become a stable system if the following condition is satisfied.

$$R_i > \frac{L}{C} \frac{P_{CPL}}{V_C^{*2}} \quad (13)$$

On the other hand, the existence of the equilibrium point in equations (5) and (6) can be ensured as in equation (14).

$$R_i \leq \frac{V_i^2}{4P_{CPL}} \quad (14)$$

Finally, the conditions in Equations (13) and (14) can be written in a single expression as given in Equation (15).

$$\frac{L}{C} \frac{P_{CPL}}{V_C^{*2}} < R_i \leq \frac{V_i^2}{4P_{CPL}} \quad (15)$$

In Equation (15), for a specific set of L values, the maximum allowable power P_{mak} be expressed as given in Equation (16).

$$P_{mak} = \min\left(\frac{V_C^{*2} R_i}{L/C}, \frac{V_i^2}{4R_i}\right) \quad (16)$$

From the above analysis, it can be concluded that the series connection of an input filter and a tightly regulated high-efficiency converter tends to instability at power values higher than a certain threshold power P_{mak} .

2.1. DC/DC Boost Converter with CPL Load in Continuous Conduction Mode

Instead of modeling a highly efficient converter with ideal regulation through CPL, it would be more appropriate to understand the behavior of converter configurations. In other words, it is essential to examine the impact of CPL on the converter operating in continuous conduction mode under both open-loop and closed-loop conditions. To achieve this, the fundamental DC/DC boost converter with a CPL load, as illustrated in Figure 3, will be analyzed.

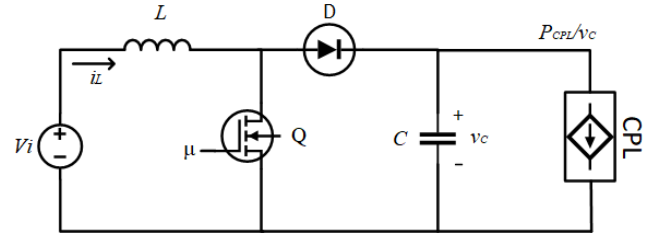


Figure 3. Basic DC/DC boost converter with CPL load.

Through simple analysis, the output voltage of a basic DC/DC boost converter is defined as shown in Equation (17).

$$\frac{d^2 v_C}{dt^2} - \frac{P}{v_C^2} \frac{dv_C}{dt} + \frac{(1-\mu)^2 v_C}{CL} = \frac{(1-\mu)V_i}{CL} \quad (17)$$

Here, μ is a binary signal; that is, during the on-time of the switch Q (T_{on}) $\mu = 1$ and during the off-time of the same switch (T_{off}), $\mu = 0$. It is clear that Equation (17) is a nonlinear differential equation. This results in the v_C voltage attempting to increase indefinitely due to the negative nonlinear damping term $-P/v_C^2$.

As seen from Equation (17), it can be concluded that the behavior of the DC/DC switched boost converter is unstable in both open-loop and closed-loop conditions without losing generality.

3. DC/DC BOOST CONVERTER WITH CPL LOAD AND VOLTAGE REGULATION USING MPC CONTROLLER

Nowadays, the MPC algorithm has been applied to most power converters (such as DC/DC, DC/AC, etc.), and the dynamic responses of boost converters in voltage control applications have been examined. The core of the MPC work is solving an optimization problem that involves the future behavior over a specific time period, considering the nonlinear states in the system. This, in turn, yields the control signal. MPC control uses predictions to compute real-time optimal control decisions, but its accuracy is hindered by system uncertainties and external factors [25]. Looking at comparison studies in the literature, the MPC technique shows better results compared to traditional methods (PI, PID, etc.). However, the performance of the MPC controller in the presence of CPL loads, compared to traditional PI control, remains unknown.

DC/DC boost converters are essential power electronic circuits commonly used to increase or “step up” the input voltage to a higher output level. These converters are especially suitable for applications involving low-voltage power sources, such as photovoltaic (PV) panels and fuel cells, where the initial voltage may be insufficient to directly power electronic loads or charge batteries. By efficiently raising the voltage, boost converters help maximize energy utilization from such sources.

The operation and control of DC/DC boost converters are fundamentally based on their switching behavior and conduction modes. Two main conduction modes are typically analyzed: Continuous Conduction Mode (CCM), where the inductor current never falls to zero, and Discontinuous Conduction Mode (DCM), where the inductor current drops to zero during part of the switching cycle. The choice between CCM and DCM affects the overall performance, efficiency, and control strategy of the converter.

In both conduction modes, the switching frequency of the converter which is the rate at which the switch turns on and off is influenced by several factors. These include the input voltage level, the desired output voltage, and the values of passive components such as the inductor and capacitors. To understand the operation of the converter more clearly, its behavior is analyzed under two distinct switching states: when the switch is on (conducting) and when it is off (non-conducting). These two conditions are depicted in Figures 4(a) and 4(b), respectively.

Active State: In this state, shown in Figure 4(a), the switch conducts current, and the inductor stores energy by building up magnetic flux. The current flowing through the inductor, denoted as “ i_L ”, increases and can be calculated using Equation (18).

$$\frac{di_L}{dt} = \left(\frac{1}{L_b}\right) (V_i - R_b i_L) \quad (18)$$

$$\frac{di_L}{dt} = \left(\frac{1}{L_b}\right) (V_i - R_b i_L - v_c) \quad (19)$$

Here, “ L_b, R_b ” represent the inductor inductance and the inductor resistance, respectively. “ V_i, v_c ” represent the input and output voltages, respectively. “ i_L ” represents the inductor current. During a switching period, the input current can be combined as shown in Equation (20), based on Equations (18) and (19).

$$\frac{di_L}{dt} = \left(\frac{1}{L_b}\right) (V_i - R_b i_L - v_c(1 - d)) \quad (20)$$

Here;

$$d = \begin{cases} 0 & \text{represents the state where the key is inactive} \\ 1 & \text{represents the state in which the key is active} \end{cases}$$

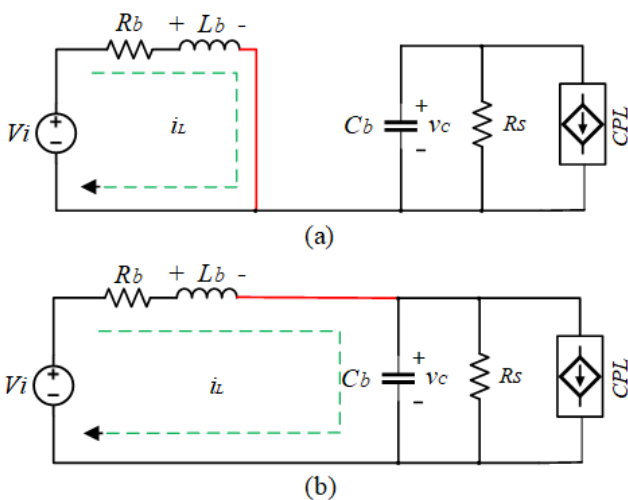


Figure 4. Circuit diagram of the converter; (a) switch active ($d = 1$), (b) switch passive ($d = 0$).

MPC is an advanced control method that determines the most appropriate control actions by predicting how a system will behave in the future. This prediction is made based on a mathematical model of the system and possible future control inputs. At each control step, MPC evaluates a range of

potential future scenarios and selects the control input that minimizes a predefined cost function, which typically represents the deviation from reference values, energy usage, or other performance criteria.

A key feature of MPC is the use of a prediction horizon (N), which defines how many future steps are considered during the optimization process. The length of this horizon is selected according to the dynamics of the system and the desired control performance. When the prediction horizon is greater than one, the controller updates its predictions at every step by shifting the horizon forward and re-optimizing accordingly [26].

In the case studied here, the prediction horizon is set to one ($N = 1$), which means that only the immediate next state of the system is considered in the optimization. This simplification is often used in power electronic applications where fast response is critical and system dynamics are relatively predictable. Accordingly, the cost function used to determine the best switching state incorporates the predicted next state of the system, the reference values, and the expected control actions. This cost function is formulated and presented in Equation(21)[27].

$$g = f(x(k), u(k), \dots, u(k + N - 1)) \quad (21)$$

The MPC method can be used in a three-stage process to derive a comprehensive cost function, as explained below [28].

- Modeling all potential switching states of the converter.
- Deriving the discrete-time model for approximations at each sampling instance.
- Defining the corresponding cost functions.

Various discretization methods are used in the literature to obtain the discrete-time model. Among these methods, the commonly used approach for first-order systems is the advanced difference Euler method, as presented in Equation (22) [28]. By combining Equations (20) and (22), Equation (23) is generated to calculate the next value of the inductor current.

$$\frac{di_L}{dt} \approx \frac{i_L(k + 1) - i_L(k)}{T_s} \quad (22)$$

$$i_L(k + 1) = \left(\frac{T_s}{L_b}\right) (V_i(k) - R_b i_L(k) - v_c(k)(1 - d)) + i_L(k) \quad (23)$$

In this context, “ T_s ” refers to the sampling time, “ k ” indicates the current iteration or sampling index, and “ $i_L(k + 1)$ ” represents the predicted inductor current for the next time step. At each sampling instant, the optimization process formulated in Equation (23) is carried out anew using the most recent set of measured data. This process determines the optimal switching state for the next interval.

It is important to note that the MPC method does not determine the optimal switching state based solely on predicted system behavior. In order to ensure accurate control, the method also aims to minimize the deviation or error between the predicted system response and the desired reference value. This step, highlighted as the third stage in the control algorithm, is essential for effective performance and is directly implemented through the cost function.

The cost function, therefore, becomes a central component in MPC based control strategies. It quantifies the error between the predicted output (e.g., current, voltage, etc.) and its reference, guiding the selection of the control action that minimizes this error.

When using the cost function defined in Equation (24), the MPC algorithm requires the calculation of this prediction error to evaluate the cost for each possible control action. The control input that yields the lowest cost i.e., the smallest error is selected as the optimal switching state for the next step. “ i_r ” in Equation (24) represents the reference current.

$$g_i(k+1) = [i_r - i_L(k+1)]^2 \quad (24)$$

During each sampling period, the fixed-step predictive control algorithm estimates the system’s future state to determine the optimal control action. However, this prediction-based approach, when implemented digitally without the use of traditional analog comparators, may cause fluctuations in the switching frequency. This variability arises because switching events are triggered based on discrete control decisions rather than fixed-frequency modulation. When the switching frequency approaches the sampling frequency, the control system may become less accurate, resulting in increased tracking error.

To address this issue and suppress unnecessary switching activity, a second term is added to the cost function specifically designed to penalize frequent switching. This term includes a weighting factor, denoted by “ λ ”, which regulates the influence of switching behavior on the total cost function. The updated cost function, which balances tracking accuracy and switching frequency, is presented in Equation (25).

By adjusting the weighting factor, it is possible to control how aggressively the algorithm avoids switching. In this study, a value of $\lambda=0.3$ was selected, based on a classification method referenced in the [29], which ensures a good trade-off between dynamic performance and reduced switching frequency.

$$g_{sw}(k+1) = \lambda[d(k) - d(k-1)]^2 \quad (25)$$

To regulate both current tracking and switching frequency simultaneously, two separate objectives must be considered each represented by an individual cost function, as discussed in Equations (24) and (25).

One of the significant strengths of the MPC approach lies in its flexibility to handle multiple control objectives within a unified framework. Instead of solving two optimization problems independently, MPC integrates both objectives into a single comprehensive cost function.

This unified function allows the controller to balance current tracking performance with the need to minimize switching activity, depending on the specific requirements of the system. The resulting combined cost function is expressed in Equation (26):

As noted in [28], using the squared error technique in multi-term cost functions leads to better outcomes, and this approach was adopted to achieve more accurate results.

$$g(k+1) = g_i(k+1) + g_{sw}(k+1) \quad (26)$$

The total cost function is computed for all possible switching states at each sampling instance. As shown in Equation (27), it is minimized. The value of “ $d(k)$ ” that minimizes the cost function is calculated using Equation (28), and the switching state is chosen accordingly based on this operation.

$$d(k) = [1 \ 0] \arg \min_d g \quad (27)$$

$$\min_{d(k)} g(k+1) = \min(g_i(k+1) + g_{sw}(k+1)) \quad (28)$$

The MPC method makes decisions about the switch position by selecting the state that results in the smallest value of the cost function. This decision-making process is crucial for determining the optimal switching state at each control interval.

For example, if the cost function corresponding to the active switch state is smaller than that of the passive switch state, the controller will select the active state as the optimal control action. This is a direct comparison between the potential future states, which avoids the need for averaging or any other statistical methods. Since the cost function already integrates all relevant system parameters, including current tracking and switching frequency, the decision is based on a straightforward evaluation of these parameters. By evaluating the cost function for each possible switching state, the MPC method ensures that the optimal control parameters are chosen for every step. This approach allows the controller to make real-time decisions that optimize system performance and maintain stability. Therefore, MPC enhances the system’s overall behavior by minimizing error while managing switching actions effectively, without any complex calculations or iterative averaging.

In summary, the optimal switching decision is made by comparing the values of the cost function, ensuring that the system’s dynamics are controlled efficiently and effectively [26].

4. SIMULATION RESULTS

The block diagram for the MPC and boost converter’s output voltage control is shown in Figure 5. To validate the effectiveness of the MPC controller, a simulation was performed in MATLAB/Simulink. The system parameters are provided in Table 1. In terms of stability, the worst-case scenario is when there is no resistive load, and the system operates with a pure CPL load. Simulation results have been obtained to measure the MPC controller’s response under different operating conditions, specifically during transitions to different power values.

TABLE I
MPC AND BOOST CONVERTER SIMULATION PARAMETERS

Symbol	Parameter Name	Value
v_{Cr}	Reference Bus Voltage	100V
V_i	Converter Input Voltage	50V
f_s	Switching Frequency	20kHz
T_s	Sampling Time	1e-06
R_s	Load Side Ohmic Resistance	50Ω
R_b	Converter Resistance	0.4Ω
L_b	Converter Inductance	648μH
C_b	Converter Capacitance	241μF
P	PI Proportional Constant	0.5
I	PI Integral Constant	200
λ	Weighting Factor	0.3

In circuits with capacitive loads, the current of the CPL (Constant Power Load) shows an inverse relationship with the bus voltage. When the voltage decreases, there is a corresponding increase in current. As mentioned in the section on CPL and instability, this leads to a negatively increasing impedance. This event causes a reduction in the system’s damping, leading to instability. Due to the nonlinear characteristics of CPLs, ensuring system stability is only possible by defining appropriate methodologies. Based on this, the objective is to design a control signal, denoted by μ , that ensures fixed-time convergence independent of initial conditions [30].

The purpose of this control signal is to ensure that the bus voltage, v_c follows the desired reference voltage v_{Cr} . To

accomplish this, the duty cycle used for controlling the boost converter through pulse-width modulation (PWM) can be determined by utilizing the signal output from the controller.

Designing such a control system is essential to ensure stability and attain the desired performance from the boost converter [31].

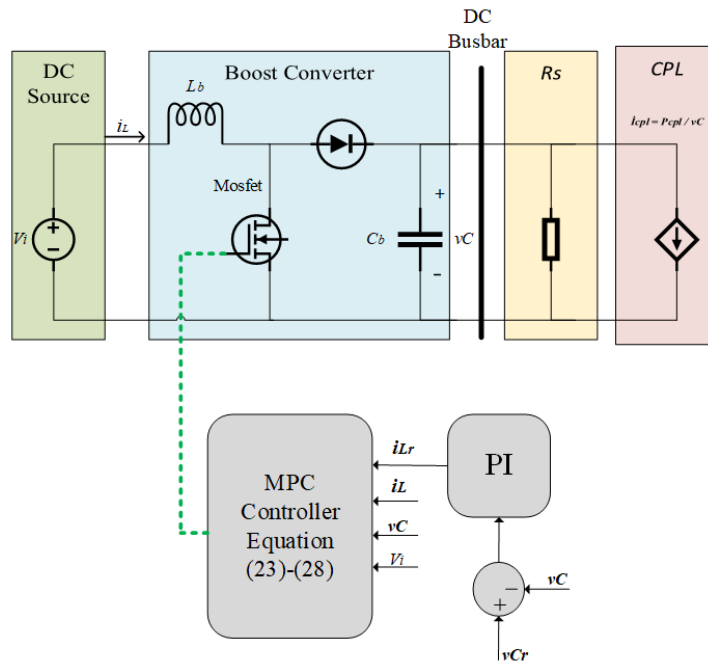


Figure 5. MPC controller block diagram.

To accurately evaluate the performance of the MPC controller, simulations were performed using a complex load model consisting of a resistive load and a constant power load (CPL) connected in parallel. The simulation results are shown in Figures 6, 7, and 8.

Initially, a 200 W resistive load and a 100 W CPL were connected in parallel to the DC supply bus. The 100 W CPL was disconnected in 0.1 seconds and reconnected in 0.12 seconds. As seen in Figure 6, the bus voltage returned to the 100 V reference value within 10 ms after each load change and remained constant thereafter.

These results demonstrate the MPC controller's fast dynamic response in handling sudden load changes, consistent with previous studies on MPC-based boost converters. Voltage overshoot during load changes is minimal, demonstrating that the controller effectively mitigates the effects of CPL-induced instability. Moreover, the rapid recovery to the reference voltage highlights the robustness of the proposed control strategy under large signal disturbances.

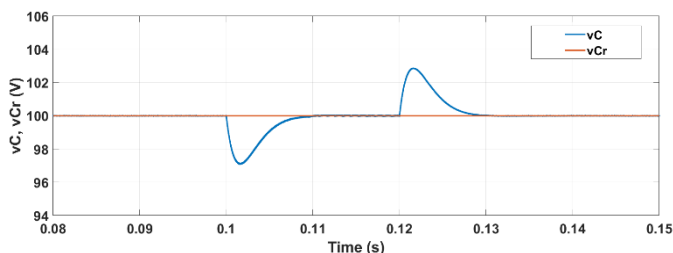


Figure 6. Response of DC link voltage to CPL load change under MPC controller

The total power drawn from the DC source during CPL power changes is shown in Figure 7. As shown, when the CPL power increases by 100 W in 0.1 seconds, the total power drawn from the source increases from 320 W to 450 W. This total power

includes the power consumed by the boost converter. When the CPL power decreases by 100 W in 0.12 seconds, the power drawn from the DC source returns to 320 W and remains constant thereafter.

These results highlight the MPC controller's ability to effectively manage sudden load changes while maintaining system stability. The smooth transition of the total power indicates minimal transient disturbances, confirming the robustness of the control strategy, consistent with previous studies on MPC-based boost converters.

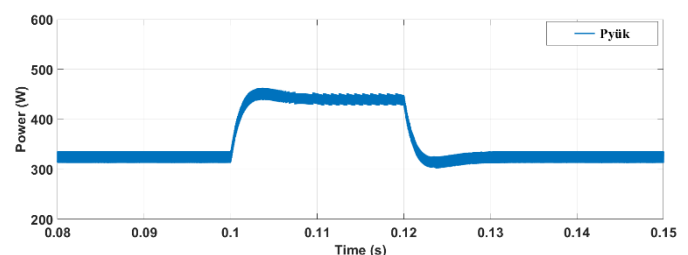


Figure 7. Change in total power drawn from the DC source under the MPC controller.

Simultaneously, the actual inductor current response compared to the reference current generated by the MPC controller is shown in Figure 8. As can be seen, the actual current actively follows the reference during CPL power changes, providing precise current regulation. The minimum deviation between actual and reference currents confirms the fast dynamic response of the MPC controller and its effectiveness in handling nonlinear load behavior.

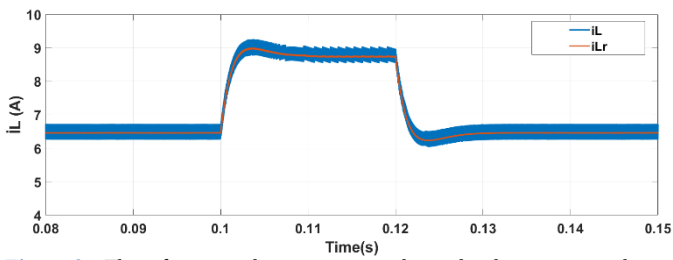


Figure 8. The reference inductor current and actual inductor current during CPL load changes under MPC control.

4.1. Comparison of MPC Control with Traditional PI Control

To evaluate the stability of the proposed MPC controller during various CPL load transitions, a comparative simulation study was conducted with a conventional PI controller. The results of this analysis are shown in Figures 10-12, and the CPL load change profile is shown in Figure 9.

As shown in Figure 9, the CPL load power increased from 100 W to 200 W in 0.1 second and decreased from 200 W to 100 W in 0.12 seconds. The primary objective was to compare the responses of the MPC and PI controllers by examining the DC boost converter output during these CPL load changes.

The simulation results show that the MPC controller exhibits faster dynamic response and better voltage regulation compared to the PI controller. During load increases and decreases, the bus voltage under the MPC returns to the reference value more quickly and with minimal overshoot, while the PI controller exhibits slower settling times and larger voltage deviations. These findings confirm the superior robustness and performance of MPC in handling nonlinear and sudden load changes.

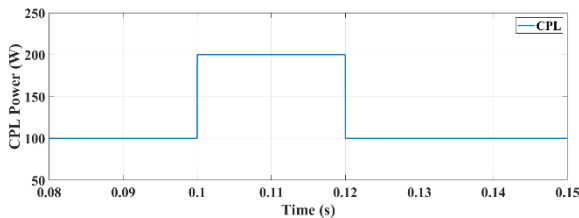


Figure 9. CPL load variation with time

It is important to note that in the comparative simulation analysis, as shown in Table 1, the DC boost converter was operated with a nominal input voltage of 50 V. As shown in Figure 9, even as the CPL power increased from 100 W to 200 W, the output voltage v_C remained constant under MPC control in Figure 10, clearly demonstrating the effectiveness of the proposed controller.

During the transition, the MPC controller exhibited a voltage drop of approximately 2.48 V, while the PI controller experienced a ripple close to 4 V. In other words, the voltage ripple under MPC was 1.52 V smaller than that of the PI controller. Similarly, when the CPL power decreased from 200 W to 100 W in 0.12 seconds, the PI controller responded similarly to the ramp period, while the MPC controller settled quickly to the reference voltage with smoother dynamics and minimal overshoot.

Moreover, while the conventional PI controller exhibited voltage fluctuations of approximately 2 V, the MPC controller-maintained fluctuations of approximately 0.1 V. This corresponds to a ripple ratio approximately 20 times lower than the PI controller and highlights the superior stability and output

voltage quality achieved with the MPC approach. These results confirm the effectiveness of the MPC strategy in handling sudden load changes and maintaining voltage stability. As a result, it is clearly evident that the traditional PI controller exhibits significantly lower performance compared to the MPC controller [32].

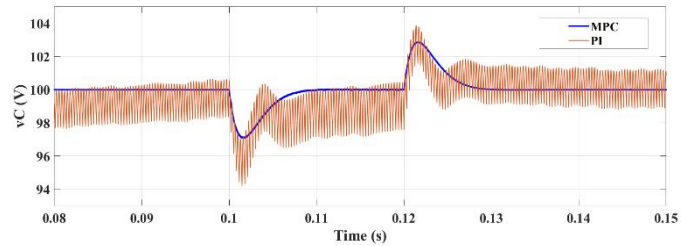


Figure 10. Comparison of DC bus voltage v_C under MPC and PI controllers.

Additionally, the total inductor current drawn by the loads, i_L is approximately 6.5 A. As the CPL power increases from 100 W to 200 W, the total current drawn by the DC boost converter from the source increases to 9 A. When the CPL power decreases by 100 W in 0.12 seconds, the current returns to 6.5 A and remains constant, as shown in Figure 11.

After each power transition, the MPC controller stabilizes the inductor current to the reference value within 10 ms, providing fast dynamic response and effective current regulation. In contrast, with a traditional PI controller, the inductor current exhibits significantly larger oscillations, similar to the behavior observed in the DC bus voltage. This comparison confirms that the MPC controller provides superior stability and tracking performance under sudden load changes, consistent with previous findings on MPC-based boost converters.

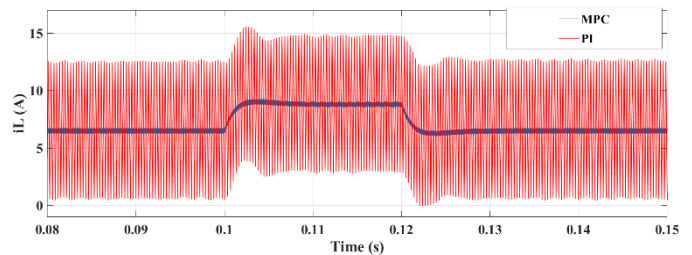


Figure 11. Comparison of coil current i_L of DC amplifier under MPC and PI controllers.

When comparing the power drawn from the source in units of P_{load} , the total power drawn under the MPC controller is approximately 650 W. When the CPL power increases from 100 W to 200 W, the total power drawn from the source increases to 900 W. When the CPL power decreases by 100 W in 0.12 seconds, the power drawn from the source drops by 600 W in a short time of 10 ms, as shown in Figure 12.

These results clearly demonstrate that the MPC controller provides a much faster and more stable response to sudden power changes compared to the traditional PI controller. The rapid adjustment of the total power demonstrates that the MPC approach effectively manages load changes while minimizing transient disturbances, confirming its superior performance compared to traditional control strategies.

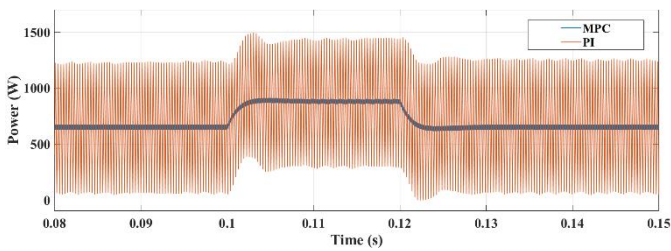


Figure 12. Comparison of power values P_{load} under MPC and PI controllers.

5. RESULTS AND DISCUSSION

In this study, an MPC controller is proposed to regulate the output voltages of DC/DC boost converters operating with a negative-impedance CPL load. The MPC controller offers several advantages, including fast dynamic response, reduced voltage swings, and high reliability under system uncertainties. The composite MPC controller used in the simulations was designed with optimized parameters to ensure precise voltage tracking.

The proposed approach provides robust resistance to CPL power fluctuations and other system disturbances, ensuring stable voltage regulation throughout the simulation scenarios. To verify the controller's effectiveness, a comparative simulation study was conducted between the MPC-based controller and a traditional PI controller. Detailed results of this comparison for standalone DC microgrids are presented in Table 2, highlighting the superior performance of the MPC strategy in terms of settling time, overshoot, and output stability.

TABLE II

DETAILED ANALYSIS OF THE DESIGNED CONTROLLER, BSC, AND MPC CONTROLLERS AGAINST CPL LOAD CHANGES.

Controllers	Settling Time		Overshoot Voltage		Oscillation Rate
	(0.1ms)	(0.12ms)	(0.1ms)	(0.12ms)	
MPC	10ms	10ms	2,91V (%2,91)	2,85V (%2,85)	0,1V
PI	14.2ms	14,2ms	5,58V (%5,58)	3,87V (%3,87)	2V

▪ It can be seen from the results that both systems are stable, but the proposed controller provides significantly better results during CPL power changes, with the MPC controller demonstrating much better settling time compared to the PI controller.

▪ Additionally, while the system under the PI controller continues to operate with high oscillations during CPL power changes, the system under the proposed controller remains stable with much smaller oscillations. As a result, the proposed controller has the advantage of superior signal stability compared to the PI controller.

6. CONCLUSION

This study introduced a Model Predictive Controller (MPC) for regulating the output voltage of DC/DC boost converters under the influence of a negative impedance Constant Power Load (CPL) in a DC microgrid. The simulation results demonstrated the effectiveness of the MPC controller in providing fast response times, reduced oscillations, and high stability, even in the presence of varying CPL power levels and system uncertainties. The MPC controller outperformed the traditional

PI controller, as evidenced by the significantly improved settling times, reduced overshoot, and smaller oscillations during power changes. Notably, the MPC controller ensured stable voltage tracking and superior signal stability compared to the PI controller, making it a more reliable solution for DC microgrids subjected to CPL fluctuations. This study highlights the promising potential of MPC in enhancing the stability and performance of power systems under challenging load conditions. Future work can explore further optimizations and real-world implementations of this control approach in diverse microgrid applications.

ETHICS COMMITTEE APPROVAL AND CONFLICT OF INTEREST STATEMENT

No ethics committee approval is required for the prepared article. There is no conflict of interest with any individual/institution in the prepared article. The data used in this article has been derived from the doctoral thesis of the author, Mustafa Güngör.

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