Unified Model Predictive Control for DC-DC Buck Converters: From Start-up to Steady-State Operation

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***Abstract*—Presented in this paper is a unified model predictive control (MPC) method for DC-DC buck converters, designed to offer stable output voltage while simultaneously regulating inductor current. Utilizing only one control loop, this method simplifies the design and regulation process and enhances dynamic performance by avoiding additional control loops. The strategy supports both start-up and steady-state conditions, providing a soft start-up process and desired stable steady-state without extra procedures. Furthermore, the algorithm is suitable for buck converters operating in both continuous (CCM) and discontinuous conduction modes (DCM). The effectiveness of this approach is validated via simulation and experimental results.**

***Index Terms*—model predictive control, dc-dc buck converter, start-up process, CCM, DCM**

I. INTRODUCTION

The rapid advancement of renewable energy and electronic technology have made power electronic converters ubiquitous. As a result, performance requirements for these converters have increased significantly [1] - [3]. Modern applications demand broader stability ranges, higher output voltage accuracy, faster load transient response, and robust over-current protection [4].

Traditional voltage-mode control for DC-DC converters is often limited by poor input and load transient responses, especially when dealing with the non-linearities and different operation modes [5]. Current-mode control for a dc-dc converter typically utilizes the inductor current in an inner loop, with an outer loop generating its reference based on voltage regulation [6]. To simplify controller design, the inner and outer loops are typically decoupled by restricting the outer controller's bandwidth to a fraction of the inner loop's bandwidth. However, this approach limits the dynamic performance of higher control levels. Additionally, tuning multiple control parameters in multi-loop systems presents significant challenges [7].

Model Predictive Control (MPC) is well-suited to meet these demands and has been successfully implemented across various power electronic topologies, including DC-DC converters [8]. And Finite Control Set Model Predictive Control (FCS-MPC) has gained widespread adoption in power converters and drives in recent years [9]. Its capability to handle multiple objectives and nonlinear control makes it particularly suitable for power electronic converters [10]. For instance, researchers have successfully applied FCS-MPC to control the output voltage of DC-DC converters [11].

Furthermore, current-mode MPC for a dc-dc converter has been developed to enhance their dynamic performance of the converter [12]. While researchers first proposed model predictive current control for boost converters [13], this implementation maintained a multi-loop architecture, merely replacing the PID module in the inner loop. This approach required a Kalman filter for the outer loop, increasing both system complexity and implementation challenges. Similarly, another proposed MPC strategy regulated inductor current but required two additional loops for indirect output voltage control [14]. A more recent NPI-MPC algorithm addressed the non-minimum phase behavior in DC-DC boost converters [15]. However, this approach utilized continuous-control set MPC and focused solely on steady-state performance.

Previous studies have not fully leveraged the multi-objective and nonlinear control capabilities of MPC. Instead, these implementations often merely substitute PI modules in the inner current control loop or require additional control modules. This multi-loop architecture increases the number of control parameters requiring tuning, thereby adding complexity to both design and implementation. Moreover, the inclusion of multiple control modules compromises the system's overall dynamic performance. Additionally, these controllers generally aim only at steady-state design and usually have a large current overshoot during the start-up.

This paper proposes an MPC method for DC-DC buck converters that synchronously controls both voltage and current. By employing MPC as a single loop, the method enhances transient performance, directly controlling output voltage and inductor current from start-up to steady-state operation in both CCM and DCM without changing the control structure. Furthermore, the integrated current regulation functionality eliminates the need for separate over-current protection and soft-start processes, thereby simplifying the hardware design. The use of weighting factors enables fully customizable control performance from start-up to steady-state.

This paper is organized as follows: Section II presents the continuous and discrete-time models of the converter and proposes the cost function design. Section III analyzes control performance through simulation and compares results with

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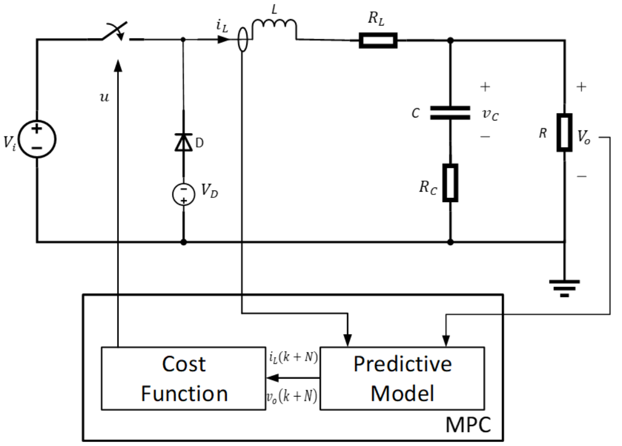


Fig. 1: Block diagram of MPC on buck converters.

other controllers. Section IV presents the experimental results, and Section V concludes the paper.

II. WORKING PRINCIPLES OF PROPOSED CONTROL STRATEGY

A. Predictive Model for Buck Converter

Fig. 1 shows the circuit topology of a dc-dc buck converter, where L is the inductance and C is the capacitance, R_L and R_C are their parasitic resistances, respectively. R is the load resistance. V_i and v_o are input and output voltage respectively. The switching state, denoted by u, assumes a value of 1 for the switch-on state and 0 for the switch-off state. The predictive model and cost function are included in the MPC block. The independent states of the converter are the inductor current and output voltage. The state vector is defined as $x(t) = [i_L(t) \; v_o(t)]^T$. Suppose that the input voltage is constant and the controlled switching state $u(t)$ is a system input, the continuous system is described by the following equations:

$$\dot{x}(t) = Ax(t) + Bu(t), \tag{1}$$

where the matrices A and B are given by

$$A = \begin{bmatrix} -\frac{R_L}{L} - (\frac{RR_C}{R+R_C}) & \frac{1}{L}(\frac{R_C}{R+R_C} - 1) \\ \frac{R}{C(R+R_C} & -\frac{R}{C(R+R_C} \end{bmatrix}, B = \begin{bmatrix} V_i \\ 0 \end{bmatrix}.$$

The dc-dc buck converter can operate in CCM and DCM, depending on the value of inductor current $i_L(t)$. Specifically, CCM refers to the case where the current $i_L(t)$ is always positive and DCM means that the current $i_L(t)$ reaches zero during the switching cycles and at that time $u = 0$. Since only the value of inductor current changes operation in DCM, the model (1) can also be applied in DCM. Besides, (1) is a nonlinear model rather than the small-signal model. Hence it can be applied to all running processes from start-up to steady state.

A discrete-time model is required for MPC implementation as an internal prediction model. For simplicity, the forward Euler's method is used, resulting in the following discrete-time model:

$$x(k+1) = A_d x(k) + B_d u(k), \tag{2}$$

where, $A_d = I + T_s A$,$B_d = T_s B$, I is the identity matrix, and T_s is the sampling period.

B. Cost Function Design

The cost function $J(k)$, detailed in (3), facilitates the optimal selection of switching state sequences for extended prediction horizons.

$$J(k) = \alpha < i_{L,err} > (k) + v_{o,err}(k) + \beta \Delta u(k). \tag{3}$$

In this specific case, the cost function encapsulates three control objectives: the average inductor current error, output voltage error, and switching frequency constraint. The averaged current error objective is represented as the average value of the inductor current over the prediction horizon, given by

$$< i_{L,err} > (k) = \frac{1}{N} \sum_{l=k}^{k+N-1} ||i_L(l) - I_L||,$$

where N is the prediction horizon and I_L is the average current reference. The output voltage objective and switching constraint are defined as

$$v_{o,err}(k) = \sum_{l=k}^{k+N-1} ||v_o(l) - V_o||,$$

$$\Delta u(k) = ||u(k) - u(k-1)||,$$

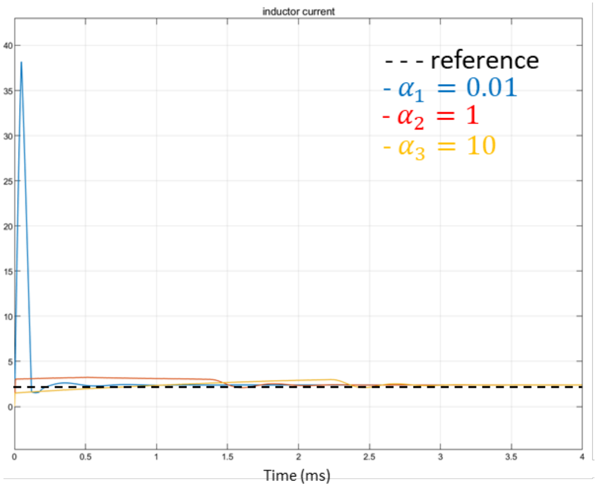
in which V_o is output voltage reference and $V_o = I_L/R$, R is the load resistance. The constraint term, the third term in (3), reduces the switching frequency to avoid excessive switching. The parameters α and β are weighting factors for inductor current and switching frequency constraints respectively.

III. ANALYSIS AND SIMULATION RESULTS

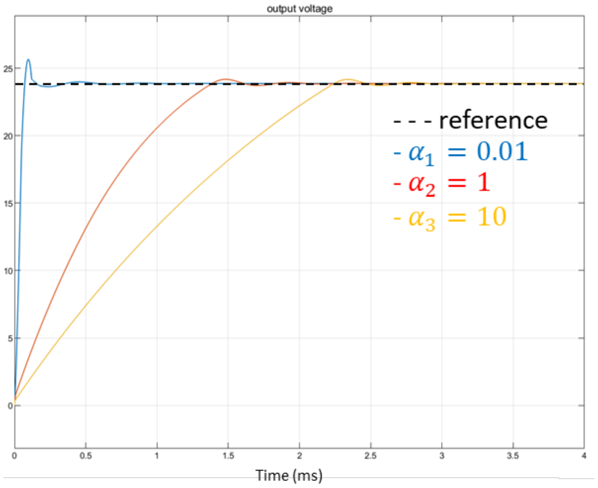
A. Weighting Factors

Unlike conventional cost functions that typically have one or two control objectives, this system incorporates three objectives, making the design of the weighting factors critical to the system's control performance.

Different combinations of weighting factors will influence the control performance relative to these three objectives. Specifically, increasing the value of α enhances the emphasis on inductor current control, while the other objectives become less significant. For the DC-DC buck converter, the primary objective is to achieve smooth and stable output voltage with over-current protection. The secondary objective is to maintain good transient performance under varying conditions. The tertiary objective is to lower the switching frequency to reduce switching losses. Consequently, the voltage error is prioritized, the current error is secondary, and switching frequency is last. Since switching loss is not the primary concern, it should be adjusted after establishing a balance between current and voltage control.



(a) Inductor current

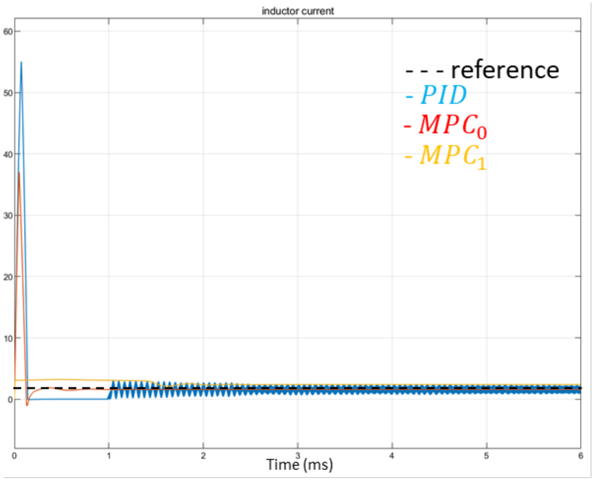


(b) Output voltage

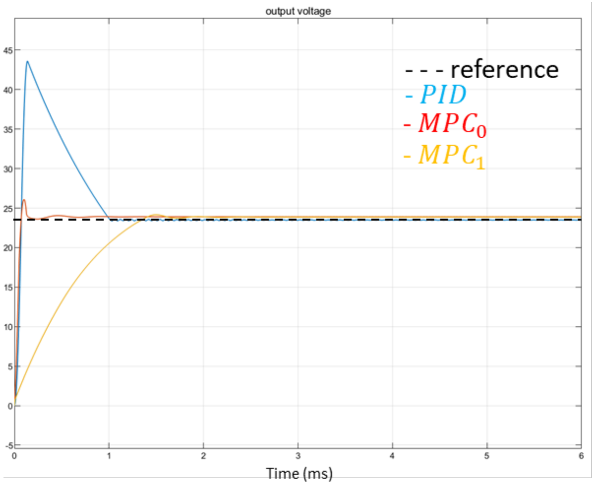
Fig. 2: Simulation results for start-up process with different weighting factors.

Fig. 2 presents the Matlab/Simulink simulation results, demonstrating the control effects on inductor current and output voltage using three different sets of weighting factors (all $\beta = 0.1$). The simulation parameters are shown in Table I. All three sets successfully reach the desired reference values, with the voltage error normalized at steady state. As shown in Fig. 2, when α_1 is set to a small value (0.1), the current control becomes limited, and the system prioritizes voltage control. This prioritization results in a large current spike—approximately 20 times the nominal current value—which could lead to inductor saturation. Such extreme current conditions would necessitate additional soft-start and over-current protection mechanisms.

However, as the current weighting increases with α_2 and α_3 (same and 10 times weighted as voltage control), the current overshoot is considerably reduced to a safe range. This adjustment, however, leads to an increased voltage settling time, due to the lower emphasis on voltage control.



(a) Inductor current



(b) Output voltage

Fig. 3: Simulation results for start-up process with different controllers.

This control algorithm effectively regulates transient performance during start-up while maintaining stable steady-state operation and offering high customizability to meet various performance requirements. Designers can achieve trade-offs between voltage and current control based on specific hardware specifications, enabling faster voltage dynamic response while maintaining inductor current within safe operating limits. And these does not require additional control modules.

B. Comparison with Other Controllers

Fig. 3 demonstrates the control performances of three different control: PID controller, conventional MPC and the proposed MPC.

As shown in Fig. 3, the PID controller (blue lines) exhibits significant overshoot in both output voltage and inductor current. This larger overshoot necessitates longer settling time to reach the desired reference values. The conventional MPC

TABLE I: Simulation and Experimental Setup Parameters

Parameters	**Values (CCM / DCM)**
Input voltage	48 V
Output voltage	24 V / 9 V
Load	10 Ω / 25 Ω
Inductance	47μH
Capacitance	94 μF
Switching frequency (PI controller)	200 kHz
PI gains	$K_p = 0.2,\ K_i = 10$
Prediction horizons	$N = 4$

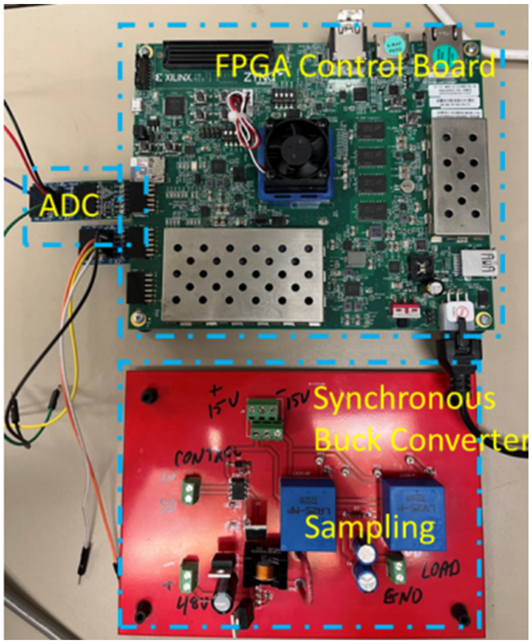
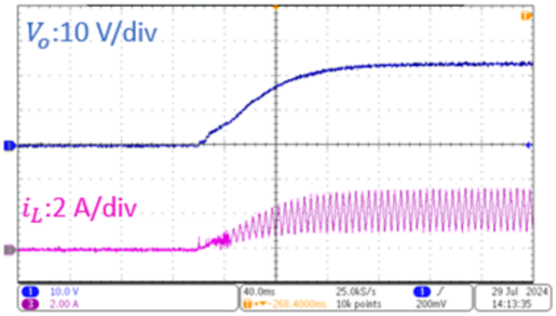


Fig. 4: Experimental setup.

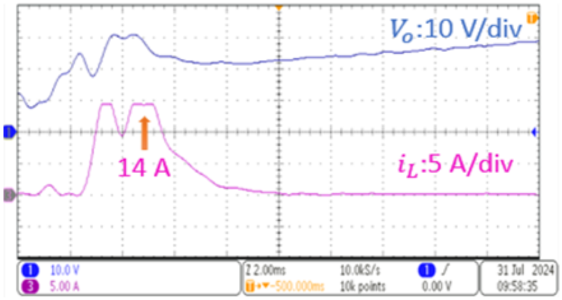
approach (red lines), which considers only output voltage control in its cost function, achieves smaller voltage overshoot and reduced settling time. However, since its control objective is limited to voltage regulation, the inductor current rises excessively as the controller attempts to reach the reference voltage as quickly as possible. The proposed MPC strategy (yellow lines) incorporates both voltage and current control objectives. This dual-objective approach maintains the inductor current within safe operating limits while effectively regulating output voltage. The settling time can be optimized by adjusting the weighting factor based on hardware-specific current overshoot tolerances.

IV. Experimental Results

To verify the proposed MPC algorithm's ability controlling voltage and current, a buck converter was built with MPC implemented on a field-programmable gate array (FPGA). The FPGA-based MPC controller uses a hardware acceleration method as described in [16]. The FPGA board is Xilinx MPSoC ZCU104, the ADC is AD7476a with 1 Msps sampling rate and the MOSFET is IRF540N. Fig. 4 is the experimental setup. Table I shows the system's parameters.



(a) proposed MPC



(b) PI

Fig. 5: Experimental results for start-up process (a) proposed MPC; (b) PI.

Fig. 5(a) illustrates the start-up process using the proposed MPC method ($\alpha = 0.5$, $\beta = 0.1$), where the output voltage and inductor current gradually reach their reference values without any overshoot or current spike. In contrast, Fig. 5(b) shows the start-up process with a PI controller ($K_p = 0.2$, $K_i = 10$), which exhibits a large current spike of around 14 A—about six times the current reference—along with a corresponding voltage overshoot. Consequently, additional processes or hardware are required to limit the over-current.

Fig. 6(a) and 6(b) demonstrate the steady-state performance in CCM and DCM, respectively. The proposed control algorithm successfully regulates the DC-DC buck converter in both operating modes using mode-specific parameters. As shown in Fig. 6, this MPC method achieves stable operation in both CCM and DCM without altering control modules.

V. CONCLUSIONS

This paper presents a novel MPC strategy for DC-DC buck converters, utilizing a single control loop to regulate both voltage and current directly. This approach not only enhances transient performance but also simplifies the hardware with stable output voltage from start-up to steady-state operation in both CCM and DCM.

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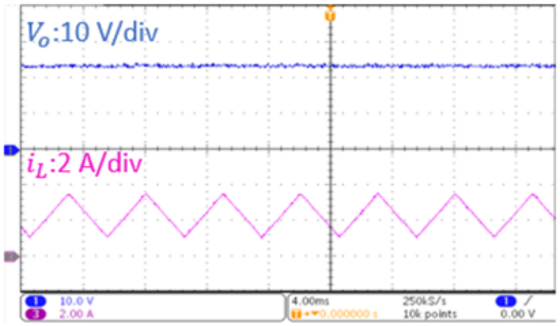
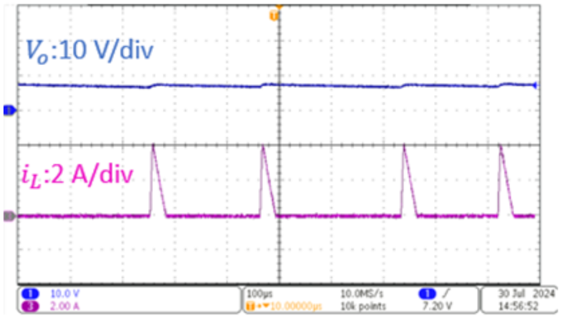


(a) CCM



(b) DCM

Fig. 6: Experimental results with proposed MPC in steady state (a) CCM; (b) DCM.

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