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# Advanced control and optimization strategies for a 2-phase interleaved boost converter

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**ABSTRACT**

Renowned for their adeptness in smoothing current flow and maintaining balanced operation, 2-phase interleaved boost converters (IBC) demonstrate remarkable efficiency, especially when confronted with demanding loads. This makes them a preferred choice for high-power applications such as renewable energy systems, high-power supplies, and electric vehicle power trains. In contrast, standard boost converters are typically favored in low-power, low-demand scenarios. The control of a 2-phase IBC involves running two boost converters in parallel but with a phase shift to reduce ripple currents, improve efficiency, and increase power handling capabilities. To ensure stability and optimal performance, the control strategies for these converters focus on achieving balanced operation between the phases. Hence, the control of 2-phase IBC presents a significant challenge due to their non-minimum phase behavior. The core focus of this article is the implementation of a composite model predictive control (MPC) technique to regulate a 2-phase interleaved boost converter. It introduces a novel approach, model predictive sliding mode control (MPSMC), which leverages the strengths of both MPC and sliding mode control (SMC). The benefits of this hybrid method, termed MPSMC, are thoroughly developed and simulated using MATLAB/Simulink. The results, as discussed in the respective section, provide an in-depth understanding of its effectiveness in practical applications.

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## 1. INTRODUCTION

A boost converter is mainly used to increase the unregulated voltage to a regulated one. Its applications can vary from battery-powered devices, renewable energy systems to automotive applications. Although there are few limitations, including voltage range, efficiency, EMI, current limitation, and control complexity. In this paper a two-phase interleaved boost converter is presented that has various advantages over a single-phase boost converter, including lower ripple current, increased efficiency, and superior power handling capabilities, especially in renewable and electric vehicle applications, as discussed in [1]–[4]. Moreover, a 2-phase interleaved boost converters (IBC) using a coupled inductor is investigated, especially for fuel cell applications, in

[5]–[7]. In addition, a phase shift switching scheme for the DC-DC boost converter with parallel switches is shown in [8].

A 2-phase IBC has two boost converter stages running in parallel but out of phase. This design comprises two boost converter stages operating in tandem, each phase-shifted for the other, ensuring concurrent operation during their switching cycles as shown in Figure 1. For simplicity, the continuous conduction mode (CCM) is being taken into consideration and the parasitic resistances for both the inductor and capacitor are also included. The phase functions are out of phase, which means that when one phase is conducting (on), the other is in the non-conducting (off) state, and vice versa. By lowering the ripple current in each individual inductor, the interleaved operation improves current sharing across phases and lowers the ripple current in the overall output voltage. Interleaving the phases minimizes ripple currents, which leads to a smoother output voltage and less stress on the components. The interleaved converter can handle greater currents more efficiently by distributing the load throughout the phases, reducing losses and boosting total converter efficiency. Ensures balanced current sharing between phases, distributing the load equally and preventing one phase from carrying the entire load. Higher power handling capacities are possible with the interleaved arrangement than with a single-phase boost converter. After elucidating the benefits of a 2-phase IBC, its imperative to examine its control mechanisms, given the inherent non-minimum phase behavior characteristic of these type of converters, which makes the control more challenging.

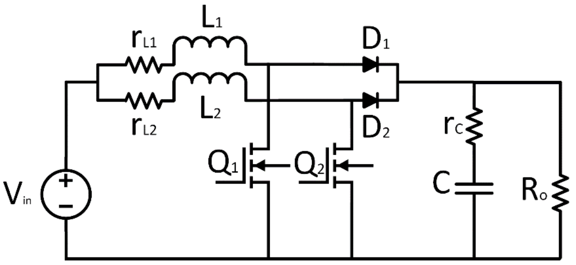

Figure 1. 2-phase interleaved DC-DC boost converter

Muktiadji *et al.* [9] show the control of the boost converter using observer-based backstepping SMC for the DC microgrid. Cunha and Pagano [10] shows some limitations in the control of the boost converter, especially in its transient behavior. This article presents an innovative model predictive sliding mode control (MPSMC) strategy to regulate a 2-phase interleaved boost converter, employing sliding mode control (SMC) within the inner loop and model predictive control (MPC) within the outer loop. This integrated control strategy substantially enhances the performance and reliability of power electronic converters, making it ideal for demanding applications such as electric vehicles, renewable energy systems, and high-performance power supplies. Samad *et al.* [11] introduced the control strategies for boost and 2-phase IBC using MPADRC that combines the advantages of MPC and active disturbance rejection control (ADRC). A proportional-integral based MPC adaptive approach was proposed for boost converters in [12], followed by the introduction of a composite adaptive MPC method in [13], designed to address model mismatches arising from parameter uncertainties and disturbances in DC-DC boost converter control designs. Furthermore, in [14], an innovative SMC coupled with a proportional integral (PI) controller was implemented to regulate a DC-DC boost converter. Although the existing literature has laid some groundwork, there remains significant uncharted territory, particularly concerning multiphase IBC.

The rest of the article is organized as follows. In section 2, we have presented the mathematical modeling of a 2-phase IBC. In section 3, we present the control and design methodology. Section 4 is about the results and discussion of our work. Finally, we have concluded the results in section 5.

## 2. MATHEMATICAL MODELING OF A 2-PHASE INTERLEAVED BOOST CONVERTER

Additionally, the distinct states that characterize a 2-phase IBC are depicted in Figures 2 to 5 each representing one of the four states as follows. In Figure 2 both switches Q1 and Q2 are on, while in Figure 3 Q1 is on and Q2 is off. In addition, Q1 is on and Q2 is off in Figure 4 and finally, Q1 and Q2 are off in Figure 5.

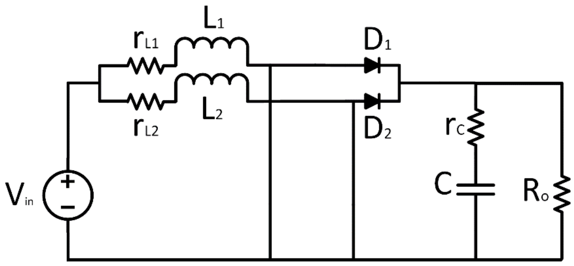

Figure 2. 2-phase interleaved DC/DC boost converter: Q1 and Q2 are on

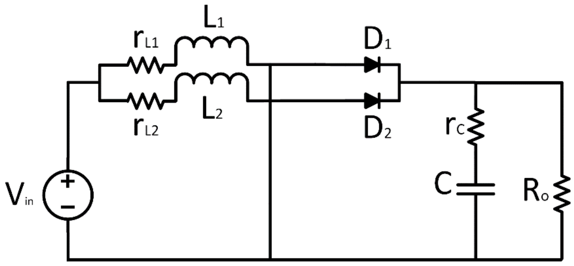

Figure 3. 2-phase interleaved DC/DC boost converter: Q1 is on and Q2 is off

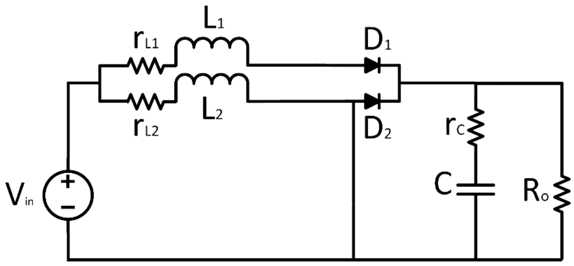

Figure 4. 2-phase interleaved DC/DC boost converter: Q1 is on and Q2 is off

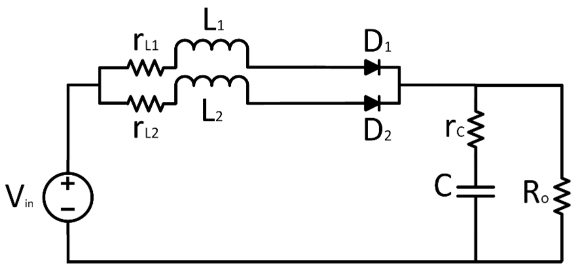

Figure 5. 2-phase interleaved DC/DC boost converter: Q1 and Q2 are off

Then using the basic rules of KCL and KVL and depending upon switch states, the current and voltage equation of all states have been formulated and for simplicity the only average state space is modeled and presented as follows, while the matrices $A_1$, $A_2$, $A_3$, $A_4$ and $B$ of all four states respectively are given by,

$$A_1 = \begin{bmatrix} -\frac{r_{L1}}{L_1} & 0 & 0 \\ 0 & -\frac{r_{L2}}{L_2} & 0 \\ 0 & 0 & -\frac{1}{R_0 C} \end{bmatrix}$$

$$A_2 = \begin{bmatrix} -\frac{r_{L1}}{L_1} & 0 & 0 \\ 0 & -\frac{r_{L2}}{L_2} & \frac{1}{C} \\ 0 & -\frac{1}{L_2} & -\frac{1}{R_0 C} \end{bmatrix}$$

$$A_3 = \begin{bmatrix} -\frac{r_{L1}}{L_1} & -\frac{r_{L2}}{L_2} & \frac{1}{C} \\ 0 & 0 & 0 \\ -\frac{1}{L_1} & 0 & -\frac{1}{R_0 C} \end{bmatrix}$$

$$A_4 = \begin{bmatrix} -\frac{r_{L1}}{L_1} & 0 & \frac{1}{C} \\ 0 & -\frac{r_{L2}}{L_2} & \frac{1}{C} \\ -\frac{1}{L_1} & -\frac{1}{L_2} & -\frac{1}{R_0 C} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{L_1} & \frac{1}{L_2} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Finally, averaging and combining the state space representation for all the states using,

$$A = (A_1 + A_3) \cdot d + (A_2 + A_4) \cdot (1 - d)$$

yeilds

$$A = \begin{bmatrix} -\frac{r_{L1}}{L_1} & 0 & -\frac{1}{2L_1} \\ -d\frac{r_{L2}}{L_2} & (d-1)\frac{-r_{L2}}{L_2} & (d-1)\frac{1}{L_2} \\ \frac{1}{C} & (2d+1)\frac{1}{C} & -\frac{1}{R_0 C} \end{bmatrix} \tag{1}$$

$$B = \begin{bmatrix} \frac{1}{L_1} & 0 \\ \frac{1}{L_2} & 0 \\ 0 & 0 \end{bmatrix} \tag{2}$$

where, $v_{\text{in}}$ is the input voltage, d represents the duty cycle, $r_{\text{L1}}$ and $r_{\text{L2}}$ are the parasitic resistances of the inductors $L_1$ and $L_2$ respectively, $D_1$ and $D_2$ are the diodes, while C is the capacitance and $r_{\text{c}}$ is the parasitic resistance of the capacitor , and $R_{\text{o}}$ is the load resistance.

## 3. CONTROL AND DESIGN METHODOLOGY

Controlling DC converters is particularly challenging due to their non-minimum phase behavior [15]. Historically, methods such as proportional integral derivative (PID), hysteresis control, voltage control, and current control have been employed. However, these techniques have limitations, including difficulty handling non-linearities and large disturbances, EMI issues, increased losses in high-frequency applications, slow response to load changes, limitations in handling varying input voltages, complex design, and excessive chattering. In contrast, the proposed method combines MPC and SMC to capitalize on the strengths of both approaches while mitigating their individual weaknesses. The key advantages of this integrated control strategy include enhanced robustness, reduced chattering, improved transient response, superior capability in handling constraints, and increased overall stability.

The amalgamation of MPC and SMC as depicted in Figure 6. The strategic utilization of MPC in the outer loop, combined with SMC in the inner loop, underscores a sophisticated approach aimed at optimizing system performance. Central to this design, the outer MPC loop is responsible for the generation of a precise reference current. Meanwhile, operating in tandem, the inner SMC loop cautiously tracks the current to its designated reference point, finally arranging control techniques in a way to achieve the best possible system performance.

To control a 2-phase IBC using MPC and SMC, the choice of using control techniques in the inner and outer loop depends on several factors, including control objectives, system dynamics, and computational requirements. This particular research uses MPC in the outer loop due to the inherent advantages like handling multivariable control objectives and constraints effectively, enabling the interleaved converters to operate in unison and producing the required system performance. Meanwhile, the characteristics like robust tracking and disturbance rejection, particularly in systems with uncertain dynamics or disturbances, make the SMC the best suitable choice to track the current in the inner loop.

Before designing a controller an objective function is required, in this particular case we took the current regulation problem as a control problem formulated as,

$$i_{L,err}(\alpha) = i_{L,ref} - i_L(\alpha) \tag{3}$$

The said objective function can be optimized by minimizing the error as follows,

$$\text{minimize } J(\alpha), \tag{4}$$

subject to the mathematical model of a 2-phase IBC. Moreover, Table 1 shows the initial and target values of the parameters used in this research work.

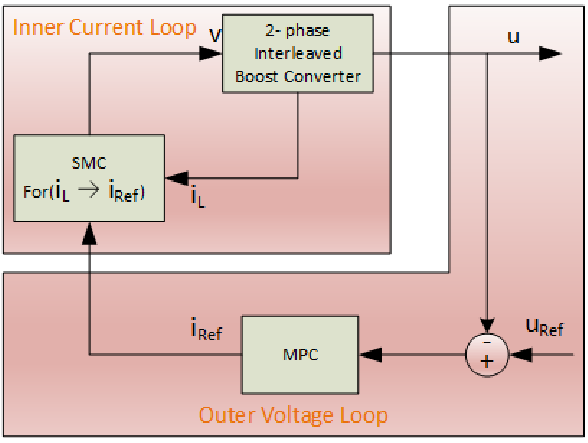

Figure 6. The proposed controller design

Table 1. Parameters used and their values

| Variable | Value |
|---|---|
| Input voltage | 12 V |
| Output voltage | 24 V |
| Duty ratio | 0.5 |
| Switching frequency | 20 kHz |
| Load resistance | 100 Ω |
| Inductance | 50 mH |
| Conductance | $1,000\,\mu$F |

### 3.1. Model predictive control

A finite-horizon and optimum control issue based on a process linear prediction model is solved by the standard MPC technique [16], [17]. Because of its simplicity in managing multivariable systems, ability to introduce input/output constraints, and user-friendly design process, MPC is becoming more and more popular in the field of power supply [18], [19]. Furthermore, the MPC is a highly effective control method based on the receding horizon control concept [20], [21]. The basic steps included are depicted as a flowchart in Figure 7.

### 3.2. Slide mode controller

Given its robustness and resilience, the SMC has emerged as a dependable control technique for attaining desired system performance, even in the presence of uncertainties and disturbances for DC-DC boost converters [22]–[26]. As suggested, the SMC is incorporated into the inner loop, where the control signals are produced using the SMC law, which adaptively modifies the duty cycles of the switches in the converter. As envisioned, the SMC can be seamlessly integrated into each phase of the 2-phase interleaved converter, adeptly regulating the inductor current and steadfastly maintaining it at the reference level, particularly within the inner loop. The control law ensures that both phases operate in synchronization, maintaining balanced operation and minimizing output voltage ripple.

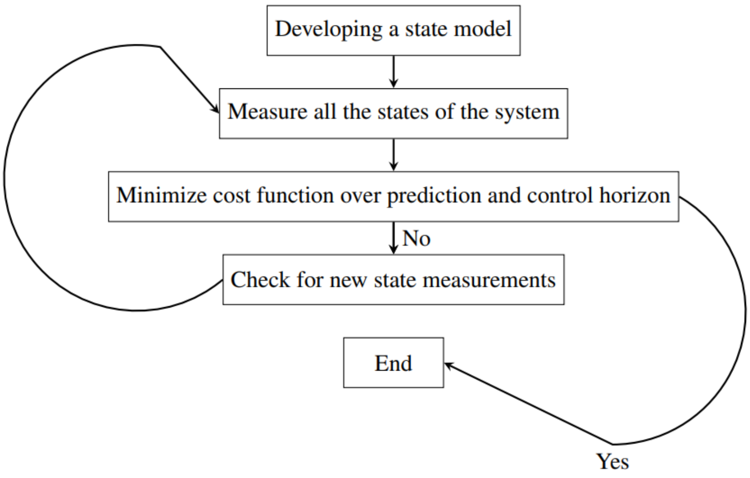

Figure 7. Flow chart illustrating the process

## 4. RESULTS AND DISCUSSION

Due to the non-minimum phase behavior, the control of these types of converters is always challenging. This particular research focuses on a novel technique that combines the advantages of MPC and SMC. The effectiveness of the proposed technique is shown in Figure 8 as compared to the step response of a 2-phase IBC without any controller in Figure 9.

In addition, it is evident from Table 2, which compares the step response parameters for both scenarios, that the proposed controller significantly improves performance. Moreover, the limitations associated with the two-phase interleaved boost converter can be effectively mitigated by implementing additional stages of interleaving in future work. Finally, the proven results in this paper demonstrate the proven effectiveness of advanced control strategies by integrating MPC and SMC. Furthermore, the effectiveness of the proposed controller is also verified by showing the response of the converter without and with controller in the presence of a disturbance as depicted in Figures 10 and 11.

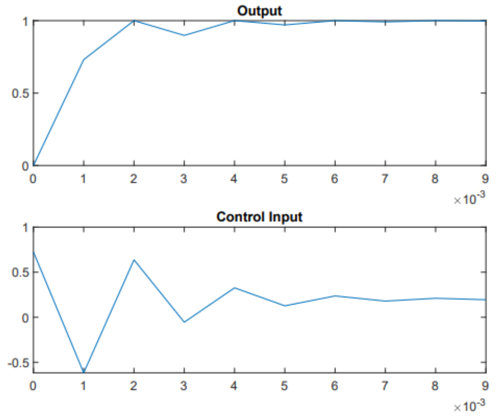

Figure 8. Step response using MPSMC controller

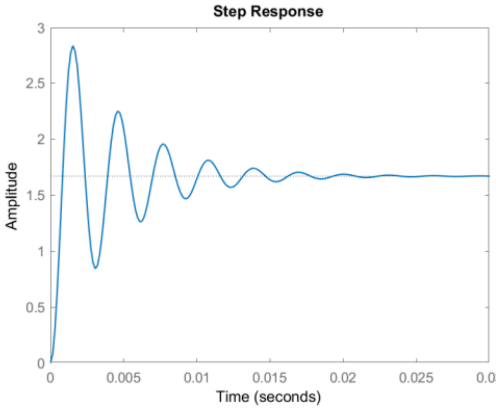

Figure 9. Step response without controller

Table 2. Comparison of step response parameters

| Step response parameter | Without controller | With proposed controller |
|---|---|---|
| Rise time (seconds) | 0.000554 | 0.0008 |
| Settling time (seconds) | 0.0171 | 0.0032 |
| Percentage overshoot (%) | 0.74 | 0.9200 |
| Final value | 1.67 | 0.9909 |

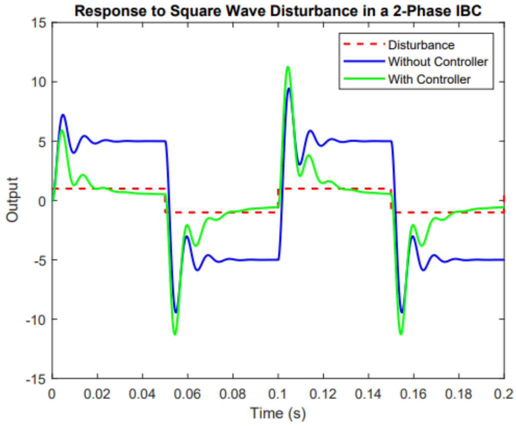

Figure 10. Disturbance as a square wave

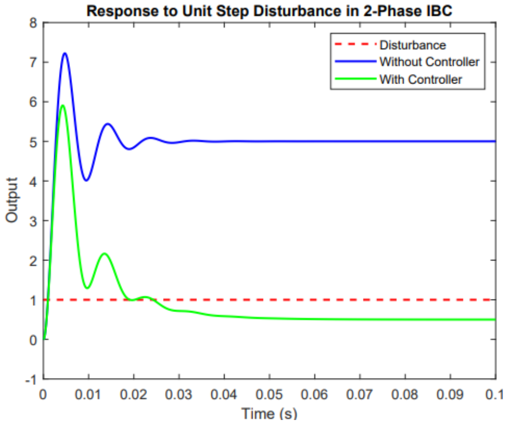

Figure 11. Disturbance as a unit step

## 5. CONCLUSION

In this paper, we proposed a novel method that combines the characteristics of MPC and SMC for the proper control of a 2-phase interleaved boost converter. 2-phase IBC is widely used in different applications because it can share current load between phases and ripple the output voltage. Control strategies for such converters are, however, very challenging as they have non-minimum phase behavior. The hybrid control method we propose combines the predictive ability of MPC to predict future behavior and optimize performance, with SMC that provides robust stability against uncertainty/disturbance. The results of our study demonstrate that the integrated MPSMC approach effectively mitigates the control difficulties associated with the 2-phase IBC. This framework integrates inner-loop SMC and outer-loop MPC, showcasing the robustness and adaptability of the devised control strategy. The combined technique offers an improved dynamic response, improved stability, and superior handling of parameter variations and external disturbances compared to conventional control methods. In conclusion, the proposed MPSMC technique represents a significant advancement in the control of interleaved boost converters. Future work will focus on further optimization and validation of the proposed control strategy in real-world applications, ensuring its robustness and effectiveness in diverse operational environments.

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