





Model Predictive Control With Stability Guarantee for the Versatile Buck–Boost Converter

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Abstract—This article presents a continuous control-set model predictive control for the versatile buck–boost converter. Unlike reported approaches in the scientific literature, our control guarantees stability in the sense of Lyapunov for a one-step horizon. The proposed strategy also demonstrates optimality and recursive feasibility. An extensive experimental set proves this control is highly efficient and stable compared to existing methods. This work gives unprecedented insights into a new generation of model predictive controls where stability is intrinsically established in the design stage.

Index Terms—Continuous control set, dc/dc converter, Lyapunov stability, model predictive control (MPC), versatile buck–boost (VBB) converter.

I. INTRODUCTION

THE versatile buck–boost (VBB) converter is considered as a power electronic building block [1] due to its ability to efficiently step-down or step-up the input voltage to a desired output voltage level, and its wide range of applications, including battery-powered devices, renewable energy systems, portable electronics, and automotive electronics [2], [3]. This bidirectional converter consists of two half-bridge MOSFETs,

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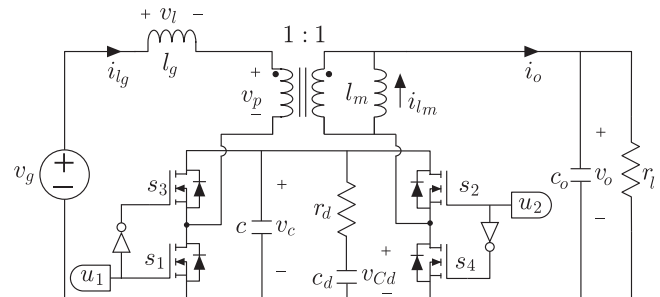


Fig. 1. Schematic circuit diagram of the VBB converter.

with $r_d c_d$ type damping network and coupled input and output inductors with a turns ratio of 1:1 as shown in Fig. 1. Previous works have shown that the VBB presents high efficiency, wide bandwidth, smooth transitions between buck and boost modes, and the ability to control input or output voltages and currents smoothly [2]. In addition to its inherent structural benefits, the VBB converter requires a well-designed control that entails performance and stability considerations [5]. Hence, model-predictive control (MPC) emerges as an ideal alternative in this context [6], since MPC has been successfully applied in motor drives [7], voltage source converters [8], and recently, in dc/dc converters [9]. While examining MPC strategies, finite control-set model-predictive control (FCS-MPC), constitutes the first generation, characterized by a one-step horizon and a direct action on the switching states of the power electronic devices [10]. This approach resembles hysteresis control, where the switching frequency is variable. The second generation of MPC is based on continuous control (CCS-MPC), utilizing a pulsewidth modulation (PWM) to achieve constant switching frequency [11]. Although the control is discrete, it operates on the modulation index instead of the switching state (see [12] for a comparison between these two approaches). A recent milestone was achieved with a CCS-MPC that guarantees stability in the sense of Lyapunov [4]. This control was successfully applied to second-order dc/dc converters [4], and this paper extends its result to the VBB converter. This extension is nontrivial since the number of inputs and the state variables in the VBB converter significantly affect the nonlinear optimization model. In addition, other contributions of this article include the following:

- 1) an MPC with stability guarantee is presented for the first time applied to the VBB converter;

- 2) although the proposed technique has been successfully used in second-order converters [4], its extension to the VBB converter is challenging due to its high-order nature ($\mathbb{R}^5 \times \mathbb{R}^2$) and the requirement for two independent control variables (u_1 and u_2);
- 3) with the proposed control technique, regulating all the converter variables with a unique equation can represent an effective alternative to multiloop controllers for the VBB converter;
- 4) the same control can be used for both the boost and buck modes of the converter without requiring the design of two independent strategies.

Notations: Functions are assumed continuous and differentiable; \mathbb{R} denotes the set of real numbers; matrices and vector functions are represented by capital letters; vectors and scalars are represented by low-case letters; entries of the matrices are also represented by low-case letters, then for a matrix $G \in \mathbb{R} \times \mathbb{R}$ we have g_{ij} ; for any vector $x \in \mathbb{R}^n$, $\|x\|$ is the Euclidean norm and $\|x\|_Q$ is $\sqrt{x^\top Q x}$ with $Q \succ 0$; symbols \succeq and \succ represent semi-definite and definite matrices, respectively.

II. REVEALING THE BILINEAR STRUCTURE OF THE VBB CONVERTER

The VBB converter is depicted in Fig. 1, and its dynamic equations are presented as follows:

$$\begin{aligned}
 c_o \frac{dv_o}{dt} &= i_g + i_m - \frac{v_o}{r_L} \\
 l_g \frac{di_g}{dt} &= v_g - (1 - u_1 - u_2)v_c - v_o \\
 l_m \frac{di_m}{dt} &= u_2 v_c - v_o \\
 c_d \frac{dv_{c_d}}{dt} &= \frac{v_c - v_{c_d}}{r_d} \\
 c \frac{dv_c}{dt} &= \frac{v_{c_d} - v_c}{r_d} + (1 - u_1)i_g - (i_g + i_m)u_2 \quad (1)
 \end{aligned}$$

where u_1 is the duty cycle of the switch s_1 and its complementary value corresponds to the duty cycle of s_3 ; u_2 represents the duty cycle of the switch s_2 , and its complementary value corresponds to the duty cycle of s_4 . In both cases $u_1, u_2 \in \{0, 1\}$. The remaining variables and parameters are easily identified in Fig. 1. This model can be written as the following bilinear dynamic system:

$$M\dot{x} = Ax + u_1 B_1 x + u_2 B_2 x + d \quad (2)$$

where $x = [v_o, i_g, i_m, v_{c_d}, v_c]$ are the state variables and matrices A and M are defined as follows:

$$M = \text{diag}([c_o, l_g, l_m, c_d, c]) \quad (3)$$

$$A = \begin{pmatrix} -1/r_L & 1 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1/r_d & 1/r_d \\ 0 & 1 & 0 & 1/r_d & -1/r_d \end{pmatrix}. \quad (4)$$

B_1 and B_2 are sparse matrices with all elements equal to zero except $B_{1[2,5]} = B_{1[5,2]} = 1$, $B_{2[2,5]} = B_{2[3,5]} = 1$ and, $B_{2[5,2]} = B_{2[5,3]} = -1$. Moreover, d is a constant disturbance given by $d = (0 \ v_g \ 0 \ 0 \ 0)^\top$. The equilibrium \bar{x} and \bar{u} for this model is given by the following expression:

$$\bar{x} = (A + \bar{u}_1 B_1 + \bar{u}_2 B_2)^{-1} d. \quad (5)$$

A discrete incremental model is defined with $\Delta x = x - \bar{x}$ and $\Delta u = u - \bar{u}$, as follows:

$$\Delta x^+ = \Lambda x + \Delta u_1 \psi_1(\Delta x) + \Delta u_2 \psi_2(\Delta x) \quad (6)$$

where Λ is the following square matrix:

$$\Lambda = I + \tau (M^{-1} A + \bar{u}_1 M^{-1} B_1 + \bar{u}_2 M^{-1} B_2) \quad (7)$$

and $\tau = 1/f_s$ is the discretization time (with f_s the switching frequency). Besides, the following affine functions are defined as follows:

$$\psi_1(\Delta x) = \tau M^{-1} B_1 (\bar{x} + \Delta x) \quad (8)$$

$$\psi_2(\Delta x) = \tau M^{-1} B_2 (\bar{x} + \Delta x). \quad (9)$$

Equation (6) represents the discrete model for the system. This nonlinear model is general for both, buck and boost operations, and for the bilinear structure of this dynamic system, the states Δx are multiplied by the input controls Δu .

III. CCS-MPC CONTROLLER WITH ASYMPTOTIC STABILITY

The proposed continuous control set model predictive control is designed based on the following nonlinear optimization model:

$$\begin{aligned}
 \min J &= \frac{1}{2} \|\Delta x^+\|_Q^2 + \frac{1}{2} \|\Delta u\|_R^2 \\
 \Delta x^+ &= \Lambda x + \Delta u_1 \psi_1(\Delta x) + \Delta u_2 \psi_2(\Delta x), \quad u_i \in \mathcal{U} \quad (10)
 \end{aligned}$$

with $Q = Q^\top \succ 0$, $R \succ 0$; \mathcal{U} is the following compact set:

$$\mathcal{U} = \{u \in \mathbb{R}^2 : 0 \leq u_i \leq 1, \text{ for } i \in \{1, 2\}\}. \quad (11)$$

The minimizer of the optimization problem (10) is given by the following expression:

$$\Delta u = \text{proj}_{\mathcal{U}} \left(- (G(\Delta x) + R)^{-1} h(\Delta x) \right) \quad (12)$$

where $G : \mathbb{R}^4 \rightarrow \mathbb{R}^{2 \times 2}$ and $h : \mathbb{R}^4 \rightarrow \mathbb{R}^2$ are functions with entries defined as follows:

$$g_{ij}(\Delta x) = \psi_i(\Delta x)^\top Q \psi_j(\Delta x) \quad (13)$$

$$h_i(\Delta x) = \psi_i(\Delta x)^\top Q \Lambda \Delta x. \quad (14)$$

Both G and R are positive definite and hence nonsingular. Therefore, the inverse of $G + R$ is well-defined. The entire control is schematically represented in Fig. 2, and the simple implementation control consists of an algebraic equation that gives the value of the modulation index. Note the simple implementation control, which consists of an algebraic equation that gives the value of the modulation index.

Remark 1: The control presented is general for both buck and boost operation modes. In fact, it can manage the transition

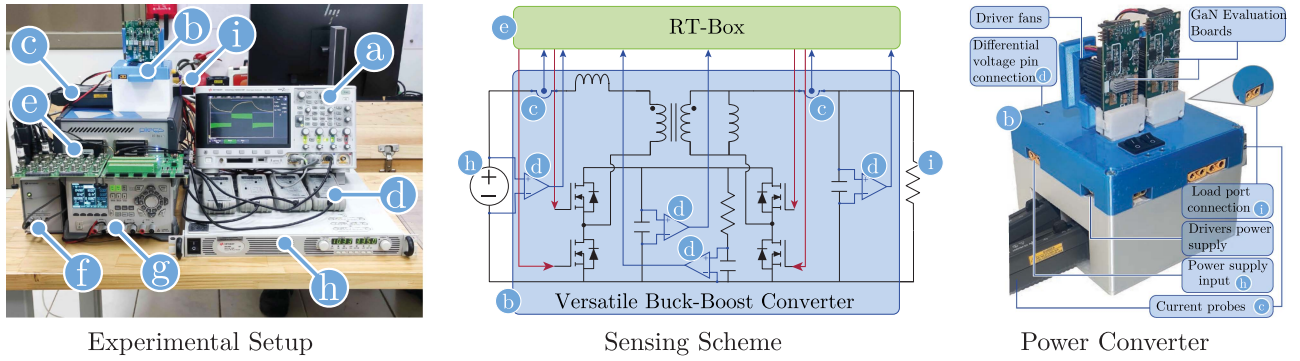


Fig. 3. (a) Oscilloscope, (b) VBB converter, (c) current probes, (d) differential voltage probes, (e) RT-Box with analog and digital breakout boards, (f) current probes power supply, (g) GaN driver power supply, (h) input voltage power supply, and (i) resistive load.

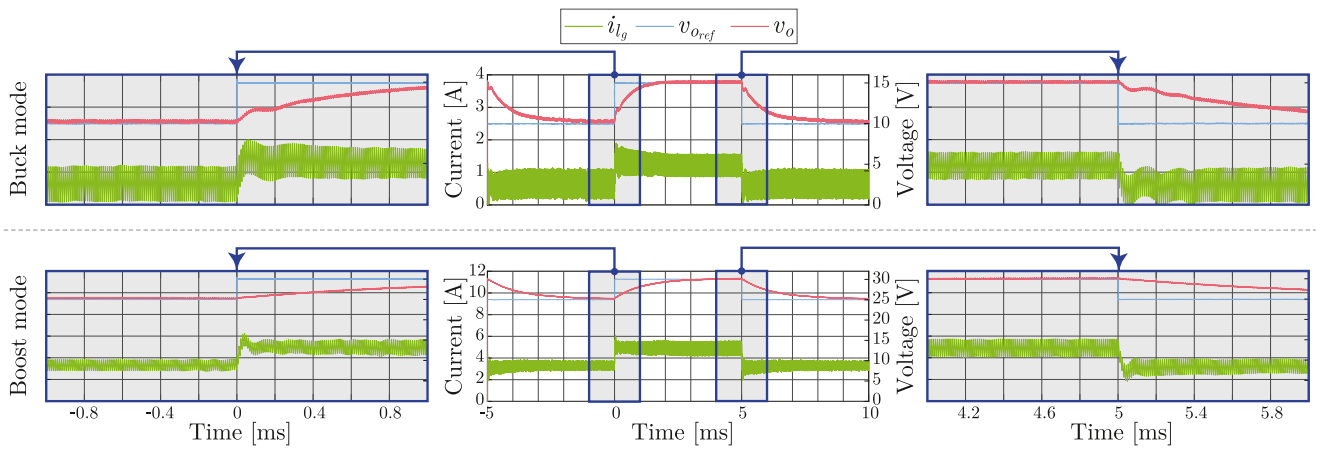


Fig. 4. Experimental results: transient response when the duty cycle reference changes from 0.5 to 0.75 and 0.5 to 0.75 for the buck mode, and when the duty cycle reference changes from 0.2 to 0.33 and 0.33 to 0.2 for boost mode.

The proposed CCS-MPC was implemented in the RT-Box of Plexim with a sampling period of $10 \mu s$ in this setup. The diagonal values of the matrix R were set at 0.1. These values are not unique. Any set of parameters for Q and R are suitable as long as they meet the conditions of Theorem 1.

Experimental results have been developed for buck and boost modes. The load used is a resistor of 10Ω and the input voltage is set at $v_g = 20 \text{ V}$. Fig. 4 shows the experimental results for the BBV converter, this experimental test presents the performance of the proposed CCS-MPC scheme for a change in the duty cycle reference from 0.5 to 0.75 and back to 0.5 in buck mode. Therefore, the output voltage reference changes from $v_{oref} = 10 \text{ V}$ to $v_{oref} = 15 \text{ V}$ and returns to 10 V , whereas the duty cycle reference is changed from 0.22 to 0.33 and 0.33 to 0.2 for the boost mode. In boost mode, the output voltage reference changes from $v_{oref} = 25 \text{ V}$ to $v_{oref} = 30 \text{ V}$, and returns to 25 V . For both modes, the output voltage accurately followed the references.

The transient for the upward voltage reference change can be appreciated in the zoomed left part of Fig. 4, where the output voltage tracks the reference, the inductor current i_g presents a faster dynamic than the output voltage, and its value is according to the resistor value. The results for downward voltage

reference change are depicted in the zoomed right part of Fig. 4, where the dynamics are very similar to the changed upward voltage reference, achieving a faster dynamic response. The experimental tests demonstrate the effectiveness of the proposed control to regulate all the variables of the converter to achieve excellent tracking performance for both modes. Fig. 5 depicts an X-Y plane between the inductor current and output voltage illustrating experimental results, wherein the reference voltage changes between operational points in a triangular manner. The figure reveals that the system stabilizes to a period-1 attractor in both buck and boost modes, indicating its tendency to revert to identical states after a defined period. Therefore, the converter presented periodic dynamics. Fig. 6 shows the mean absolute percentage errors (MAPE) for the proposed control; variations on the capacitance, resistance, and inductance in each operation mode for the converter were considered. The proposed control showed low sensitivity to the converter's parameter variations. The control achieved the reference and remained stable for the output voltage and the inductor current variables in all cases. Fig. 7 shows an experimental dynamic response of the proposed CCS-MPC strategy and a FCS-MPC. The FCS-MPC employed a sample time of $5 \mu s$ to correspond to an equivalent switching

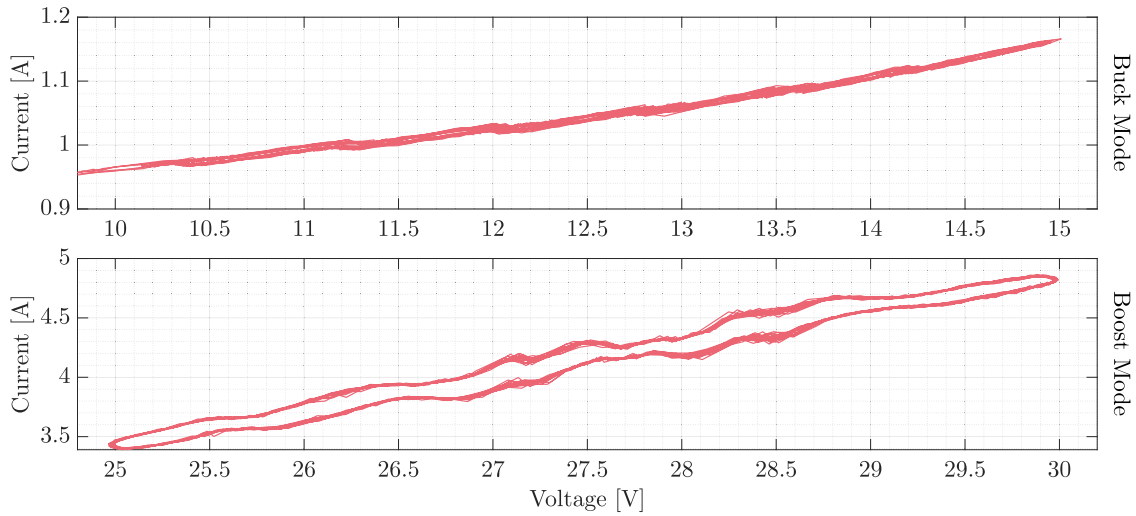


Fig. 5. X-Y graph that illustrates the relationship between current and voltage as the voltage reference transitions between operation points in a triangular manner. The system exhibits periodic behavior with a single cycle, showing repetitive oscillation between a specific set of states in a regular pattern. This pattern repeats continuously over time.

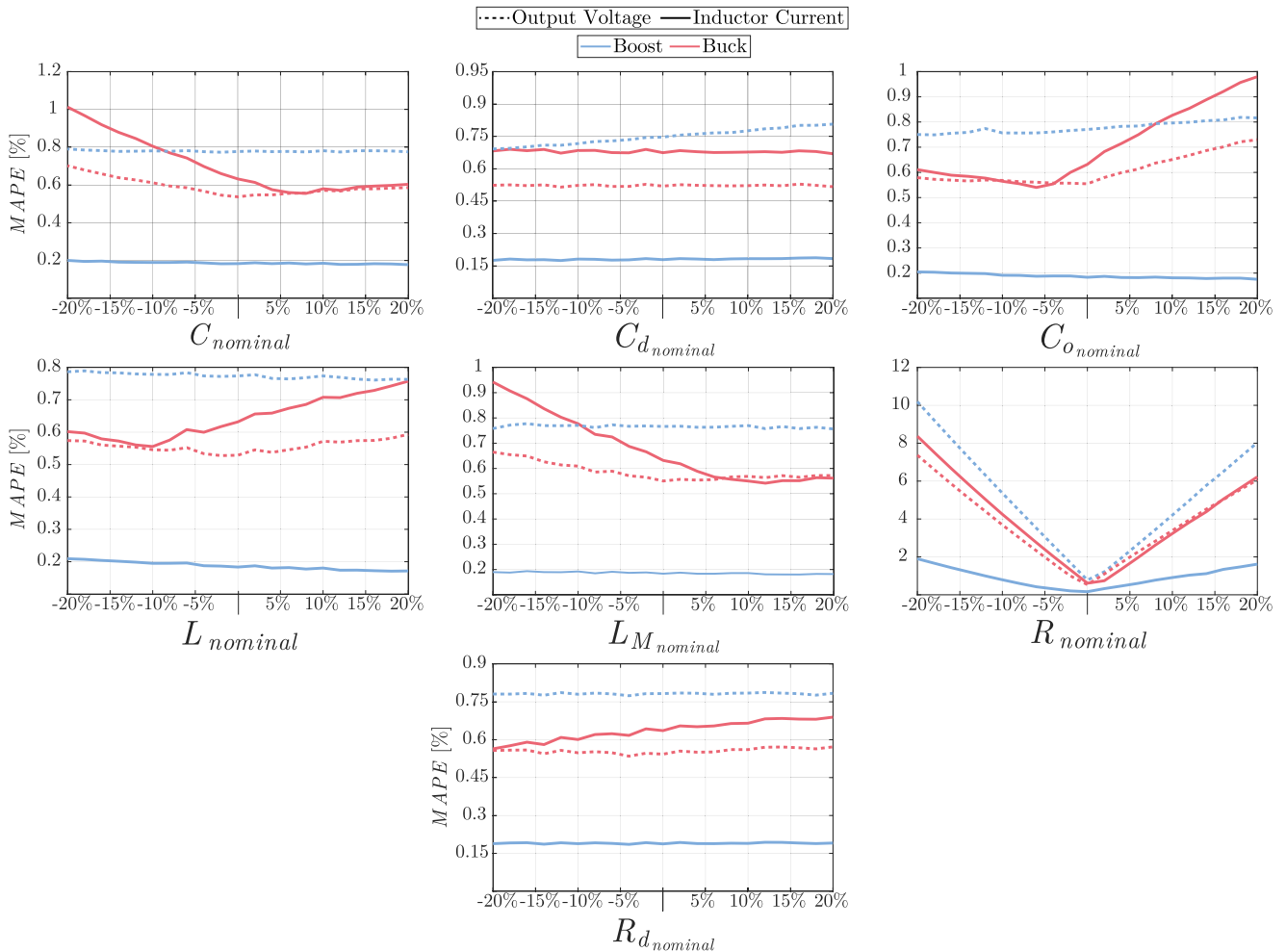


Fig. 6. MAPE of the proposed MPC when there is variation in the parameters of the converter in buck and boost mode for the output voltage and inductor current.

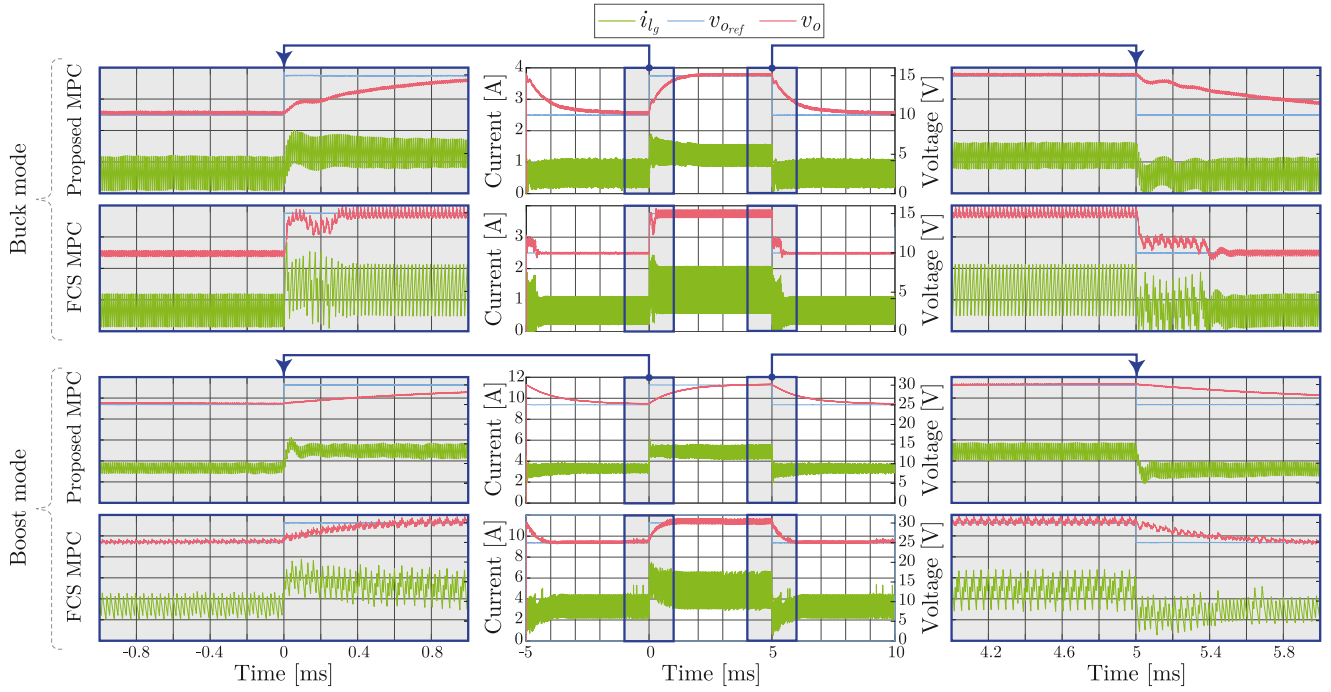


Fig. 7. Comparison between the proposed MPC and the classical Finite Control Set MPC using identical voltage references. The FCS MPC employs a sample time of $5 \mu\text{s}$ to obtain a maximum switching frequency of 100 kHz.

TABLE II
CONTROLLERS COMPARISON

	Voltage ripple [V]	Current ripple [A]	Current overshoot [%]
Proposed MPC			
Buck	0.44	1.09	17.35
Boost	0.23	1.41	14.42
FCS-MPC			
Buck	1.41	1.63	50.75
Boost	2.46	3.78	21.93

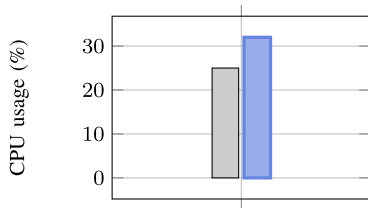


Fig. 8. Comparison in CPU usage between the proposed CCS-MPC (■) and FCS-MPC (■).

frequency of 100 kHz. The results comparison of the controllers are shown in Table II, where the MPC outperformed the FCS-MPC when subjected to identical voltage reference changes, exhibiting superior voltage and current ripple, as well as improved overshoot and undershoot characteristics. Finally, Fig. 8 illustrates a comparison of CPU utilization between the proposed MPC and the FCS-MPC approach. The proposed controller uses 32% of the CPU, whereas the FCS-MPC utilizes 25%.

This signifies a 7% increase in CPU usage with the proposed controller.

V. CONCLUSION

A continuous control set model predictive control was introduced for the regulation of all variables of the VBB converter. This topology offers appealing advantages, such as a wide output voltage range, higher performance achievement, and gaining more interest in power electronic applications. The proposed control strategy has the advantage of improving the robustness of predictive control with fixed frequency and stability guarantee for the VBB converter. The optimization model resulted in a relatively simple equation that can be easily implemented, and experimental results demonstrate superior performance for variation of reference values. The response to reference changes shows a fast dynamic speed for the VBB converter in both buck and boost operation modes. As part of our future work, we intend to conduct a comprehensive comparative analysis to evaluate the cost-effectiveness between GaN and MOSFETs in our specific application.

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