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REGULAR ARTICLE

Performance Analysis of Boost Converter Using Model Predictive Controller

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Model Predictive Control (MPC) has emerged as a powerful control strategy for power electronics applications, particularly in DC-DC converters, due to its ability to handle system constraints and optimize performance in real time. The boost converter is a crucial component in many power electronic systems, widely used in renewable energy systems, electric vehicles, and industrial applications. Achieving high efficiency and dynamic performance in such converters is a significant challenge due to the non-linear and time-varying nature of the system. This study describes how to effectively regulate a DC-DC boost converter voltage using a Model Predictive Controller (MPC). The boost converter, widely used in power electronics for stepping up voltage levels, requires precise control to ensure optimal performance, especially under varying load and input conditions. Traditional control methods often struggle with nonlinearity and rapid dynamic changes, leading to performance degradation. MPC, with the flexibility to tackle multi-variable control issues and forecast future actions using a system model, offers a robust solution. By continuously solving an optimization problem at each sampling interval, MPC adjusts the control input to maintain the desired output voltage while respecting system constraints. Simulation results demonstrate that MPC outperforms conventional control methods by improving transient response, reducing steady-state error, and enhancing the overall efficiency of the boost converter. The proposed approach also showcases the controller's adaptability to real-time disturbances, making it a promising technique for advanced power electronic applications.

Keywords: Boost converter, Model predictive controller, DC–DC converter, Feedback control, PID Controller, Ripple reduction.

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1. INTRODUCTION

Power converter utilisation has grown significantly over the last few decades for an extensive range of uses, such as distributed generation, energy conversion, motors, and traction [3]. This type of equipment converts an electrical signal to deliver power to the electric machinery. Within the power circuit family, DC-DC converters are among the most crucial circuits. Because of their inherent nonlinearity, these systems offer a fascinating area for control algorithms [1]. First, the boost-type converter exhibits intrinsic instability and non-minimum phase characteristics. Second, system uncertainties, including dynamic load demand, input voltage fluctuation, and other circuit parameter fluctuations, might negatively impact voltage regulation. Investigating an efficient control law is therefore crucial to guaranteeing the boost converter's performance [2]. Power converters have been the subject of numerous control schemes throughout the years, most of them are based on the traditional proportional-integral-derivative (PID) controller in conjunction with PWM. The PWM blocks ensure a decoupling between the switching and sampling times, permit fixed frequency operation, and prevent the need for a switching model. Control design of boost converters is complex due to their non-minimum phase characteristics and inherent nonlinearity. Accurate voltage regulation is hindered by system uncertainties such as dynamic load demands and input voltage variations. MPC is a potent method that ought to satisfy the modern power converters' demands for the enhanced performance and efficiency. MPC's optimisation capabilities have recently piqued the curiosity of the academic and research sectors.

A prominent controlling technique that has been applied in numerous engineering domains is MPC [4]. MPC is appropriate for managing power converters owing to an abundance of its properties. Constraints, nonlinearities, and the multivariable anticipation might all be readily incorporated into the mathematical equation besides to being simple and intuitive. However, the computational cost is higher than that of standard linear control methods since an open-loop optimum problem is solved at each sampling instant. In order to address this issue, many MPC types have been proposed in the literature [5]. This point is particularly significant when it comes to power converters. It has been implemented in this industry with enormous accomplishment by virtue of the advent of robust embedded systems with greater processing capabilities [12].

The present study addresses the difficulties caused by nonlinearity and quick dynamic changes in power

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electronic systems by designing a Model Predictive Controller (MPC) for the precise regulation of a DC-DC boost converter using optimal voltage regulation from the crucial MPC algorithm [17]. Finally we demonstrate the adaptability of the MPC to real-time disturbances while ensuring robust operation within system constraints in advanced power electronic application.

This paper's work focuses on applying the MPC technique to boost converters and examines how changes in controller performance impact of its scenarios for modifications. Additionally, a comparison between PID and MPC controllers is presented. The work's section-by-section details are as follows: Section II provides an overview of the Boost converter's operation, design, and state space model. An overview of MPC Design is provided in Section III & Section IV presents the MPC algorithm outline while Section V presents the discussion of simulation findings. Section VI presents conclusion drawn from the simulation work.

2. DESIGN AND ITS ANALYSIS OF BOOST CONVERTER

2.1 Design of Boost Converter

As seen in Fig. 1, a boost converter is a DC-DC converter that raises (boosts) a lower input voltage to a higher output value. The boost converter operates in the ON phase during inductor charging: Energy is stored in the inductor as current passes through it when the switch is closed. The moment this will occur, the output capacitor supplies the current to the load. When the switch is opened, the inductor reverses its polarity and adds its stored energy to the input voltage, which raises the output voltage. This process is known as inductor discharge (OFF phase) [6].

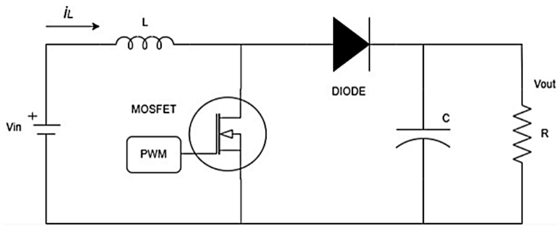

Fig. 1 – Boost converter circuit diagram

2.2 Analysis of Boost Converter

The discrete-time model of a boost converter, we use state-space modeling and convert it into the discrete domain [7]. The boost converter state-space model is shown in equation 2.1, 2.2,

ON State (u=1)

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \tag{2.1}$$

OFF State (u=0)

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -1/C \\ 1/L & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \tag{2.2}$$

Combine ON and OFF States using a duty cycle (D), the combined state-space model is in equation 2.3,

$$\frac{dx}{dt} = A_c x + B_C V_{in} \tag{2.3}$$

Where, $x = \begin{bmatrix} i_L \\ V_c \end{bmatrix}$

$$A_c = D\, A_{ON} + (1 - D) A_{OFF}$$

$$B_c = D\, B_{ON} + (1 - D) B_{OFF}$$

For digital control implementation, the continuous-time model is discretized in equation.2.4, 2.5

$$x[k+1] = A_d x[k] + B_d V_{in}[k] \tag{2.4}$$

$$y[K+1] = C_d[K] \tag{2.5}$$

Where,

$$A_d = e^{A_C T_s}$$

$$B_d = \int_0^{T_S} e^{A_c \tau}\, B_c\, d\tau$$

Ts is the sampling time

$e^{A_C T_s}$ - Matrix Exponential

3. METHODOLOGY

3.1 Design of Linear Model Predictive Controller

In a boost converter, MPC's goal is typically to minimise control efforts and prevent system saturation while regulating the output voltage to a reference value, $V_{ref.}$ [11]. Prediction Model: Use the discretized equations to predict the future states of inductor current iL and output voltage Vo over prediction horizon [15].
The cost function J to minimize can be defined as in equation.6:

$$J = \sum_{K=1}^{N} \left(\left(V_0[K] - V_{ref}\right)^2 Q + \left(D[k] - D_{ref}\right)^2 R \right) \tag{3.1}$$

Where,
N – prediction horizon.
V_{ref} – reference output Voltage.
D_{ref} – reference duty cycle.
Q & R are positive definite weighting matrices that enforce deviations from the reference trajectory & excessive control strategies. In MPC based control of boost converter, there are several constraints to consider such as,

State Constraints are given in equation 3.2, 3.3,

$$i_{Lmin} \le i_L[k] \le i_{Lmax} \tag{3.2}$$

$$V_{omin} \le i_L[k] \le V_{0max} \tag{3.3}$$

Control Input Constraints are given in equation 3.4, 3.5,

$$D_{min} \leq D[k] \leq D_{max} \tag{3.4}$$

Where,
D_{min} & D_{max} represent the minimum and maximum duty cycle

$$\min_{(D_1, D_2, D_3 \ldots D_m)} J = \sum_{K=1}^{N} \left(\left(V_0[K] - V_{ref} \right)^2 Q + \left(D[k] - D_{ref} \right)^2 R \right) \tag{3.5}$$

To facilitate a clear understanding of the MPC algorithm, a comprehensive flowchart detailing its outline is presented in Fig. 2, serving as a step-by-step guide for practical implementation.

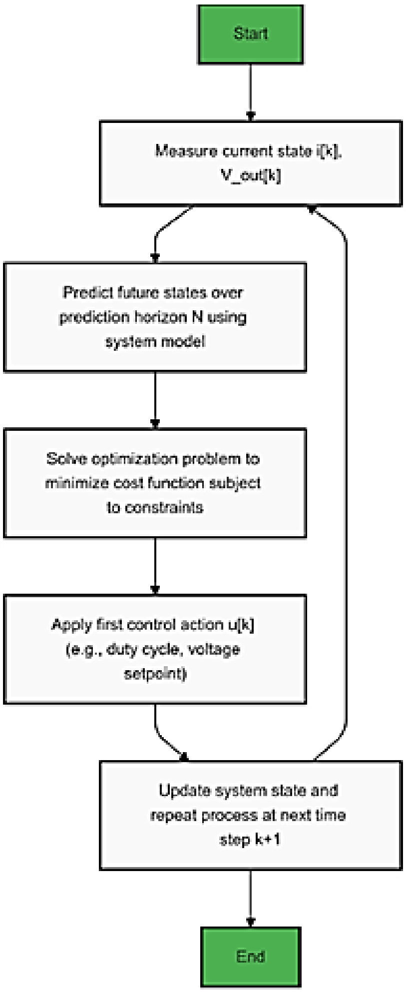

Fig. 2 – Flowchart of MPC algorithm

4. SIMULATION RESULTS AND ITS ANALYSIS

Fig. 3 displays the block diagram of the boost fed using the MPC controller. A boost converter with a feedback control mechanism is depicted in this diagram. A greater output voltage V_{out} across the load is achieved by stepping up the input voltage V_{in}. The feedback system is made up of an MPC controller that creates a control signal for the PWM (Pulse Width Modulation) block to regulate the MOSFET by comparing the reference voltage V_{ref} with V_{out} [16]. Despite variations in load, the output voltage is guaranteed to remain at the optimum level owing to the closed-loop design. Table 1 lists the boost converter circuit parameters used in the simulation investigation. Additionally, the MPC controller parameters and Ziegler-Nicholas tuned PID (ZN-PID) are given. Both controllers have been established on the boost converter in order to compare their voltage tracking performance [17].

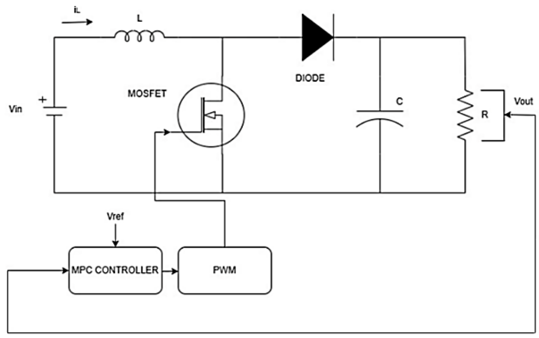

Fig. 3 – Block diagram of boost fed with MPC controller

Table 1 – Parameters of Boost converter

Parameter	**Value**
Input Voltage	12 to 24 Volts
Output Voltage	600 Volt
Switching Frequency	100kHz
Duty Ratio	0 to 1
Inductor	38.86mH
Capacitor	670 µF
Load Resistance	3600 ohm

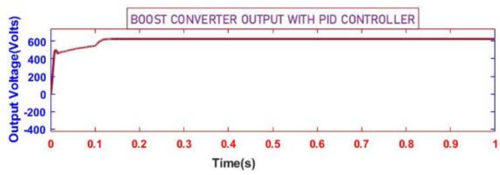

Fig.4 – Boost converter output voltage with PID controller

The Fig. 4. Represents the V_{out} response of a boost converter controlled using a PID controller. The voltage starts from zero and rises rapidly toward the desired value of 600 V. This shows the transient response of the system, where the PID controller works to bring the output voltage to the setpoint. There is a slight overshoot above 600 V during the initial transient phase. This is common in PID controllers and indicates the system's tendency to exceed the setpoint momentarily before stabilizing. After around 0.2 seconds, the output voltage stabilizes at the expected value of 600 V. The controller eradicated the steady-state error, maintaining the output voltage despite any disturbances or load variations. If there were input voltage disturbances, the controller compensates for them effectively, ensuring the output remains constant. The tuned PID controller parameters as given below,

Proportional gain (K_P = 0.6), Integral gain (K_i = 0.05), Derivative gain (K_D = 0.05)

4.1 PID Controller Performance

Fast Settling Time: The system stabilizes quickly

(~ 0.2 s). Minimal Overshoot: The overshoot is small, indicating the PID parameters are well-tuned. Stable Output: The controller maintains the output at the desired voltage without oscillations

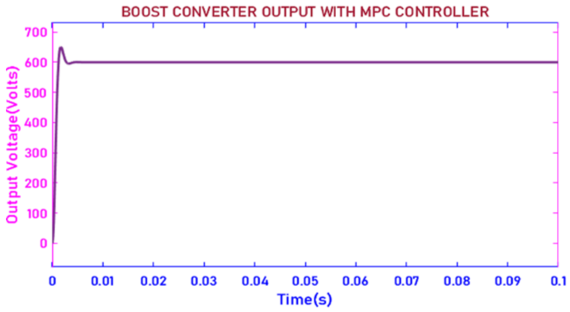

Fig. 5 – Boost converter output with MPC controller

The Fig. 5 represents the output voltage response of the boost converter controlled with an MPC. The output voltage starts at 0 V and rises quickly to approach the desired value of 600 V. There is a small overshoot in the response where the voltage exceeds the desired value momentarily. The output voltage slightly exceeds 600 V before stabilizing. This indicates the dynamic response of the MPC during transients. The magnitude of the overshoot appears to be minimal, reflecting good performance of the MPC. The voltage stabilizes at 600 V within approximately 0.04 seconds. This shows that the system has a fast settling time, which is desirable for power electronics applications. The output voltage remains steady at 600 V, with no observable oscillations. This indicates that the MPC is effectively maintaining the desired output voltage despite potential input or load variations. The tuned MPC controller Parameters are given below.
Prediction horizon (PH): 10, Control horizon (CH): 2 Input constraints [$u_{\min}$, $u_{\max}$]: [0,1], input disturbances [$V_{0\min}$, $V_{0\max}$]: [12, 24].

4.2 MPC Controller Performance

Fast and Stable Response: The system quickly achieves and maintains the setpoint. Minimal Overshoot and Oscillations: The MPC Provide excellent transient and steady-state performance. Good Robustness: The output voltage remains stable indicating that the MPC handles system dynamic well.

Finally, the performance of the boost converter is compared under PID and MPC control strategies, with key performance parameters such as transient response, summarized in Table 2 for a comprehensive evaluation.

Table 2 – Comparison of PID and MPC controller performance parameters with existing system

Controllers	Rise time(sec)	Settling time (T_s) (sec)	%Overshoot
Proposed PID Controller	0.1	0.2	6.67%
ProposedMPC Controller	0.02	0.04	1.67%
Conventional ZN-PID@ Ref. [4]	0.5	27.8 m	6.98%
Conventional MPC @ Ref. [4]	0.04	4.4 m	4.67%

5. CONCLUSION

The application of Model Predictive Control (MPC) for DC-DC boost converter regulation demonstrates its superiority over traditional control methods. By leveraging a predictive model and real-time optimization, MPC effectively addresses the challenges posed by the nonlinearity and rapid dynamics of boost converters. Simulation results confirm that MPC significantly improves transient response, minimizes steady-state error, and enhances system efficiency while maintaining operation within system constraints. Additionally, its adaptability to disturbances ensures robust performance under varying load and input conditions. These findings establish MPC as a promising and advanced control strategy for modern power electronic applications, offering both precision and reliability.

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Аналіз продуктивності підвищувального перетворювача з використанням модельного прогнозуючого контролера

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Модельно-прогнозируюче керування (MPC) стало потужною стратегією керування для силової електроніки, особливо в перетворювачах постійного струму (DC-DC), завдяки своїй здатності обробляти системні обмеження та оптимізувати продуктивність у режимі реального часу. Підвищувальний перетворювач є ключовим компонентом у багатьох системах силової електроніки, широко використовується в системах відновлюваної енергії, електромобілях та промислових застосуваннях. Досягнення високої ефективності та динамічних характеристик у таких перетворювачах є значним викликом через нелінійну та змінну в часі природу системи. У цьому дослідженні описано, як ефективно регулювати напругу підвищувального перетворювача постійного струму за допомогою модельно-прогнозируючого контролера (MPC). Підвищувальний перетворювач, широко використовується в силовій електроніці для підвищення рівнів напруги, вимагає точного керування для забезпечення оптимальної продуктивності, особливо за змінних умов навантаження та вхідного сигналу. Традиційні методи керування часто мають проблеми з нелінійністю та швидкими динамічними змінами, що призводить до погіршення продуктивності. MPC, завдяки гнучкості у вирішенні проблем багатозмінного керування та прогнозуванні майбутніх дій за допомогою системної моделі, пропонує надійне рішення. Безперервно розв'язуючи задачу оптимізації на кожному інтервалі дискретизації, MPC регулює вхідний сигнал керування для підтримки бажаної вихідної напруги, дотримуючись системних обмежень. Результати моделювання демонструють, що MPC перевершує традиційні методи керування, покращуючи перехідну характеристику, зменшуючи похибку усталеного стану та підвищуючи загальну ефективність підвищувального перетворювача. Запропонований підхід також демонструє адаптивність контролера до збурень у реальному часі, що робить його перспективним методом для передових застосувань силової електроніки.

Ключові слова: Підвищувальний перетворювач, Модельний прогнозуючий контролер, DC-DC перетворювач, Керування із зворотним зв'язком, PID-регулятор, Зменшення пульсацій.