

**JOURNAL GEUTHEE OF ENGINEERING AND ENERGY**

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# Model predictive control for buck boost converter to improve BLDC motor stability

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**ABSTRACT**

Brushless Direct Current (BLDC) motors are widely employed in industrial automation and electric vehicles. However, mechanical load variations can cause output voltage fluctuations, increased ripple, and reduced stability of the DC–DC converter supplying the motor. This study proposes Model Predictive Control (MPC) for a Buck–Boost converter to improve voltage regulation and the dynamic performance of a BLDC motor drive. The system was modeled in MATLAB/Simulink and evaluated under resistive loads of 150–650 Ω, with and without the controller, and under mechanical load torques of 10–50 N·m. Without the controller, the output voltage varied between 305 V and 327 V with a voltage ripple of 3.41–9.72%. With MPC, the output voltage remained within 314–315 V for all resistive loads, the voltage ripple decreased to 0.044–0.178%, and the inductor current ripple was below 0.12%; however, a steady-state error of 4.67–5.00% relative to the 300 V reference remained. In the BLDC motor drive, the stator current increased from 5.961 A to 31.32 A and the electromagnetic torque from 11.7 N·m to 53.37 N·m as the load increased, while the rotor speed decreased from 1821 rpm to 577 rpm. The controller achieved rise times of 0.011–0.030 s and settling times of 0.030–0.080 s, whereas the output voltage varied from 356 V at light load to 307 V at full load. The proposed MPC substantially reduces voltage and current ripple and provides a fast, stable transient response, but further tuning is needed to remove the steady-state offset and improve voltage regulation at light loads.

**Keywords: Model Predictive Control (MPC), Buck Boost Converter, BLDC Motor, Voltage Ripple, Dynamic Performance**

*Manuscript received 07 July 2026; revised 07 Nov 2026; accepted 12 Nov 2026..*
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## 1. INTRODUCTION

Buck boost converter is a series of electronics that can quickly increase/decrease the voltage. It depends on the duty ratio of more than 50% the converter will increase the voltage (boost), while if the duty ratio is less than 50% the converter will decrease the voltage (buck). This capability provides high flexibility in power settings, making buck boost an essential component in a wide range of technology applications. Duty cycle settings in addition to being able to set the conversion value also buck boost converters have many advantages, including having good voltage flexibility and voltage stability although it has many advantages, buck boost converters also have some significant drawbacks, one of the main problems is unstable performance when facing load variations or changes in input voltage. [1]

Conventional controllers are designed for the linear systems; hence, a linearized model in the neighborhood of the converter nominal operating point is used. Therefore, for a stable conventional controller, a significant change in the operating point might lead to system instability. Moreover, the other drawback of conventional controllers is that decreasing the overshoot percentage increases the rise time. [3] Controllers, such as Proportional–Integral (PI) and Proportional–Integral–Derivative (PID), have been widely adopted in DC–DC converter applications because of their simple structure and ease of implementation. However, these controllers are generally designed using linearized models around nominal operating points, making their performance degrade under nonlinear operating conditions, parameter uncertainties, and load variations. Consequently, voltage fluctuations, increased ripple, slower transient response, and reduced regulation accuracy may occur when the converter operates under dynamic conditions. Recent studies have therefore shifted toward nonlinear and optimization-based control strategies capable of predicting future system behavior and maintaining robust performance under varying operating conditions.[2]

Susilo et al. designed and simulated a PID-controlled Buck–Boost converter to regulate the output voltage under varying input voltage and load conditions . The simulation was carried out using Proteus 8.9 with PID parameters of Kp = 1.0, Ki = 0.01, and Kd = 0.1. The results showed that the proposed controller successfully maintained the output voltage close to the 24 V reference even when the input voltage varied from 12 V to 40 V, producing an output voltage error below 5%. In addition, the converter was able to maintain relatively stable output voltage under variable load conditions, demonstrating the effectiveness of PID control for output voltage regulation. However, the controller performance strongly depended on the tuning of the PID parameters, and different gain values resulted in output voltages that failed to reach the desired setpoint.[3]

Moai et al. implemented a Buck–Boost converter with a soft starter to regulate the speed of a DC motor using MATLAB/Simulink. The proposed method successfully maintained the motor speed at 1750 rpm by adjusting the converter duty cycle according to load variations, while the soft starter limited the starting current to less than 20 A. The study also demonstrated that increasing the duty cycle compensated for the reduction in motor speed caused by increasing mechanical load. However, the converter operation relied on manual duty-cycle adjustment, and no automatic voltage regulation strategy was employed. Furthermore, the study did not investigate advanced control techniques, such as Model Predictive Control (MPC), nor did it evaluate converter dynamic characteristics including voltage ripple, rise time, settling time, or steady-state voltage regulation under dynamic operating condition[4]

Recent studies have demonstrated that Model Predictive Control (MPC) has become one of the most promising control strategies for power electronic converters because of its capability to predict future system behavior and determine the optimal switching action while satisfying system constraints. Danyali et al. [5] proposed an MPC-based control strategy for a buck–boost inverter in photovoltaic applications and reported significant improvements in output voltage regulation, transient response, and tracking accuracy under varying operating conditions. Ullah et al. [14] developed a Direct Model Predictive Control (DMPC) algorithm for a non-inverting buck–boost DC–DC converter and showed that the controller avoided the dead zone near the transition between the buck and boost modes while improving response time, reference tracking, and overshoot compared with classical control techniques. Li et al. [15] proposed an MPC strategy for a four-switch buck–boost converter in which the modulator and mode-detection scheme were replaced by cost-function optimization, achieving smooth mode transitions without an additional mode-transfer design. These studies indicate that MPC provides superior dynamic performance and voltage regulation compared with conventional controllers, making it a promising control technique for high-performance DC–DC converter applications.

Despite these advances, several research gaps remain. First, the MPC studies in [5], [14], and [15] focused on the converter itself rather than on a Buck–Boost converter supplying a Brushless Direct Current (BLDC) motor, whereas Buck–Boost-fed motor drives have mainly been studied with PID control or manual duty-cycle adjustment [3], [4], although advanced control techniques for BLDC motors have been widely reviewed [6]. Second, the effect of

mechanical load variation on both the converter output voltage and the motor response has rarely been evaluated within a single control framework. Third, quantitative comparisons between an uncontrolled and an MPC-controlled Buck–Boost converter under identical load conditions, including the voltage error and ripple, are seldom reported. To address these gaps, this study proposes an MPC-based Buck–Boost converter for BLDC motor applications. The specific contributions of this study are: (i) the design of an MPC-based Buck–Boost converter supplying a BLDC motor in MATLAB/Simulink; (ii) a quantitative comparison between the uncontrolled and the MPC-controlled converter under five identical resistive loads in terms of output voltage error, voltage ripple, and inductor current ripple; and (iii) a comprehensive evaluation of the converter and motor dynamic characteristics, including output voltage, stator current, rotor speed, electromagnetic torque, rise time, and settling time, under five mechanical load torques from 10 to 50 N·m.

## 2. RESEARCH METHOD

### 2.1. Research Design

This research employed a simulation-based quantitative approach to evaluate the performance of a Model Predictive Control (MPC)-based Buck–Boost Converter supplying a Brushless Direct Current (BLDC) motor under various mechanical loading conditions. The entire system was modeled and simulated using MATLAB/Simulink. The study focused on analyzing the converter output voltage regulation and the dynamic performance of the BLDC motor through transient response analysis

### 2.2. System Configuration

The overall configuration of the proposed control system is illustrated in Figure 1. The system integrates a Buck–Boost converter, a Model Predictive Control (MPC) algorithm, and a BLDC motor drive to achieve stable voltage regulation under varying load conditions. The Buck–Boost converter functions as the DC–DC power conversion stage, while the MPC controller continuously predicts the future converter behavior and determines the optimal duty cycle to maintain the output voltage at the reference value of 300 V. The regulated DC output is then supplied to the BLDC motor, whose performance is evaluated under different mechanical load conditions.

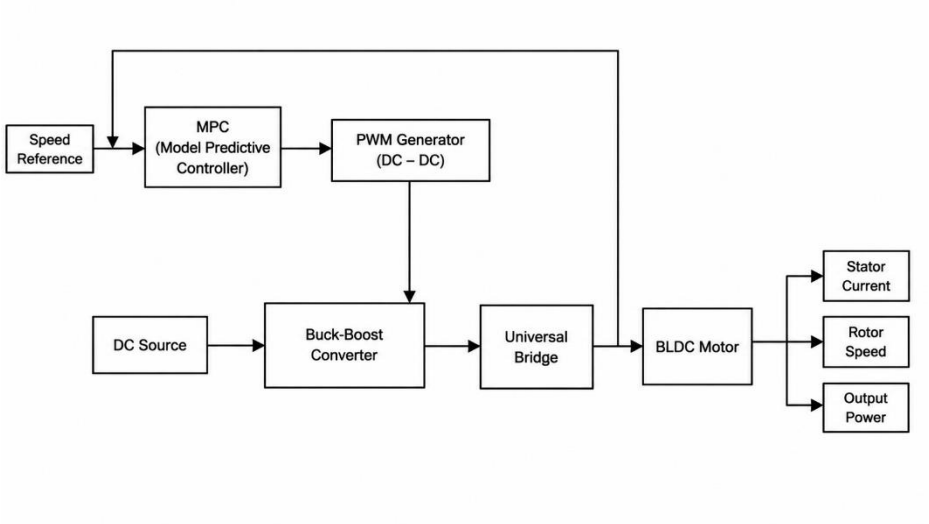



Figure 1. Block diagram of the proposed control system

As shown in Figure 1, the input DC voltage is applied to the Buck–Boost converter, where the switching operation is controlled by the duty cycle generated by the MPC algorithm. The controller receives feedback from the converter output voltage and compares it with the reference voltage. Based on the prediction model and the optimization cost function, the MPC computes the optimal control action at each sampling instant. This closed-loop control strategy enables the converter to compensate for load variations, reduce voltage ripple, suppress transient overshoot, and provide a stable DC voltage to the BLDC motor.

### 2.3. Mathematical Model

#### 2.3.1. Mathematical Model of the Buck Boost Converter

The Buck–Boost converter is a DC–DC power converter capable of producing an output voltage that is either higher or lower than the input voltage by adjusting the switching duty cycle. The converter operates in two switching states, namely the ON-state and OFF-state of the MOSFET switch.[7] In its application, performance buck-boost converter It is greatly affected by the variation of duty cycles and changes in load. Changes in the duty cycle will change the MOSFET's switching time so that it has a direct impact on the output voltage. Meanwhile, load changes can affect the system's dynamic response, such as the emergence of Overshoot, recovery time, and output voltage fluctuations. This condition is an important concern, especially in power supply systems that require voltage stability under various operating conditions. [8] Based on these operating modes, the mathematical model can be expressed using the state-space representation as follows.

- Condition On :

$$vl = Vin \tag{1}$$

- Condition Off :

$$vl = -Vo \tag{2}$$

By using the principle of volt-second balance in a steady state condition, the relationship between output voltage, input voltage, and duty cycle is obtained as follows :

$$Vo = -\frac{D}{1-D} Vin \tag{3}$$

Inductor current Equation :

$$I_o = \frac{P_o}{V_o} \tag{4}$$

Average inductor Current, for a buck boost converter :

$$I_L = \frac{I_o}{1-\mathrm{D}} \tag{5}$$

The inductance is calculated by :

$$L = \frac{V_{in} D}{\Delta I_L f_s} \tag{6}$$

The output capacitor is used to reduce the output voltage ripple. Its capacitance is calculated as follows

$$C = \frac{I_o D}{\Delta V_O f_s} \tag{7}$$

### 2.3.2. Mathematical Model of Model Predictive Control

Models Predictive Control (MPC) operates as a control technique with discrete time intervals, using a process model of a system. The goal is to predict the future behavior of the process in order to achieve optimal closed loop control measures, by minimizing objective functions within a limited time horizon and certain limitations. MPC calculations generate values that are used as a solution to optimization problems real-time.[9] The prediction horizon N2 must be long enough to represent the effect of a change in the manipulated variable u on the control variable y. Delays can be considered by the lower prediction horizon N1 or by incorporating them into the system model lower prediction horizon is set to N1 = 1 to account for the computation time (hence the computation is conducted in one time step, the solution u is implemented not before the next time step). The Time-Optimal MPC is implemented by minimizing the cost function N, subject to the state and input constraints. The solution is the minimum-horizon feasible trajectory, corresponding to the most time-efficient maneuver the system can perform under the given constraints.[10]

MPC allows forus to define the resulting behavior of the vehicles using a cost function and a prediction horizon. However, the optimization-based methods are accompanied by a high numerical effort, especially for the nonlinear vehicle dynamics considered here. Efficient methods for the treatment of such problems have been developed.[11] The mathematical model

of the Buck–Boost converter is discretized using the sampling period Ts to obtain the discrete-time state-space model required for the implementation of the MPC algorithm.

- Prediction Model

$$x(k+1) = Ax(k) + Bu(k) \quad (8)$$

- Cost Function

The MPC controller minimizes the following quadratic cost function:

$$J = \sum_{i=1}^{N_p} \left(y_{ref}(k+i) - y(k+i)\right)^2 + \lambda \sum_{i=1}^{N_c} \left(\Delta u(k+i)\right)^2 \quad (9)$$

Where:

- $Np = prediction\ horizon$
- $Nc = control\ horizon$
- $\lambda = weight\ factor$
- $y_{ref} = reference\ output\ voltage$
- $\Delta_u = change\ in\ duty\ cycle$

### 2.3.3. Mathematical Model of BLDC Motor

Brushless Direct Current (BLDC) motors are widely used because they offer high efficiency, high torque, and low noise levels. Compared to conventional DC motors, BLDC motors have several advantages. One of the main advantages is that brushless motors use semiconductor devices to perform commutation and reverse the motor rotation direction. As a result, the motor operates more smoothly, which significantly reduces noise levels. In addition, BLDC motors provide better efficiency and require less maintenance than conventional DC motors and induction motors.[12] BLDC motors are permanent magnetic synchronous motors in which the motor control is supplied with a DC power source, and to drive the rotor part of the motor is supplied by a three-phase AC power source. BLDC motors have two parts, namely the rotor which is the moving part and the stator which is the stationary part.[13] The BLDC motor model consists of electrical and mechanical dynamics.

Electrical equation :

$$V = Ri + L\frac{di}{dt} + e \quad (10)$$

Back emf :

$$e = K_e\omega \quad (11)$$

Electromagnetic torque :

$$T_e = K_t i \quad (12)$$

Mechanical equation

$$J\frac{d\omega}{dt} = Te - Tl - B\omega \quad (13)$$

Where :

- J = rotor Inerta
- B = Viscous friction coefficient
- $T_L$ = Load torque
- $\omega = rotor\ speed$
- $K_e$ = Back EMF constant
- $K_t$ = Torque constant

## 2.4. Research Procedure

This study employed a simulation-based research approach to evaluate the performance of the proposed Model Predictive Control (MPC) strategy applied to a Buck–Boost converter supplying a Brushless Direct Current (BLDC) motor. The research was carried out using MATLAB/Simulink to analyze the converter performance and motor dynamic response under different operating conditions. The research procedure consists of several sequential stages, including literature review, mathematical modeling of the Buck–Boost converter and BLDC

motor, MPC controller design, simulation development, performance testing under different mechanical loads, data acquisition, and result analysis. The overall research procedure adopted in this study is illustrated in Figure 2. The flowchart summarizes the sequence of activities performed from system modeling to performance evaluation.

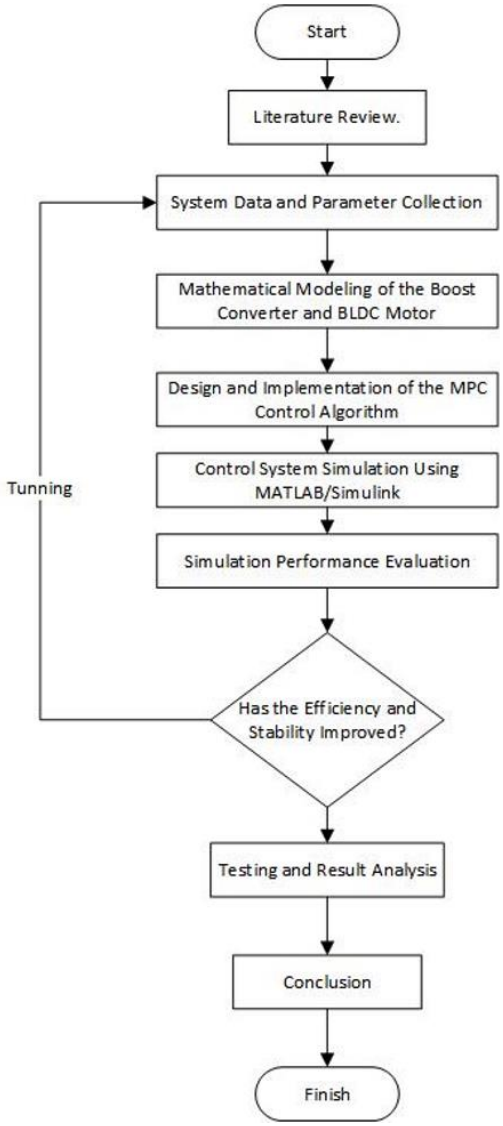



Figure 2. Research flowchart

## 2.5. Simulation Parameters

The proposed Buck–Boost converter and BLDC motor drive system were modeled and simulated using MATLAB/Simulink. The simulation parameters were selected according to the converter design specifications and the rated operating conditions of the BLDC motor. These parameters were used consistently throughout all simulation scenarios to ensure a fair evaluation of the proposed Model Predictive Control (MPC) strategy under different loading conditions. The electrical parameters of the Buck–Boost converter, the BLDC motor specifications, and the tuned MPC controller parameters are summarized in Tables 1–3.

Table 1. Buck–Boost converter parameters

| No. | Parameters | Symbols | Parameters | Units |
|---|---|---|---|---|
| 1 | Inductance | L | 2 | H |
| 2 | Capacitance | C | 2.2 | F |
| 3 | Switching Frequency | F | 20.000 | Hz |
| 4 | Load Resistance | R | 60 | Ohm |

| | | | | |
|---|---|---|---|---|
| 5 | Input Voltage | Wine | 220 | V |
| 6 | Refrence Output Voltage | Vout | 300 | V |
| 7 | Duty Cycle | D | 58 | % |

A BLDC motor was employed as the load to evaluate the effectiveness of the proposed MPC-controlled Buck–Boost converter under different operating conditions. The motor parameters were selected according to the rated specifications provided by the MATLAB/Simulink BLDC motor model. These parameters were maintained constant throughout all simulation scenarios and are summarized in Table 2.

Table 2. BLDC motor parameters

| No. | Parameters | Symbols | Parameters | Units |
|---|---|---|---|---|
| 1 | Stator Resistance | $R_s$ | 2.8750 | Ω |
| 2 | Stator Inductance | $L_s$ | 8.5e-3 | $H$ |
| 3 | Magnetic Flux | $\lambda$ | 0.175 | $Wb$ |
| 4 | Back EMF Flat area | - | 120 | Degrees |
| 5 | Rotor Inertia | $J$ | 0.8e-3 | $kg.m^2$ |
| 6 | Viscous Friction Coefficinet | F | 1*10-3 | $N.m.s$ |
| 7 | Pole Pair | P | 4 | - |

The performance of the proposed Model Predictive Control (MPC) depends on the appropriate selection of weighting factors, operating constraints, and control parameters. These parameters were obtained through an iterative tuning process to achieve accurate voltage tracking, reduced overshoot, improved steady-state performance, and stable converter operation under varying load conditions. The tuned MPC parameters used in this study are presented in Table 3.

Table 3. Parameters of the proposed Model Predictive Control

| No. | Parameters MPC | Value |
|---|---|---|
| 1 | Tracking Weight | 20 |
| 2 | Overshoot Penalty | 3000 |
| 3 | Overshoot Lock | 1200 |
| 4 | Smoothness Weight | 1.5 |
| 5 | Voltage Constraint Weight | 8000 |
| 6 | Current Constraint Weight | 2 |
| 7 | Maximum Voltage | 350 |
| 8 | Sampling Time | $5 \times 10^{-6}$ |
| 9 | Integral Gain | 0.0003 |
| 10 | Sampling Time | |
| 11 | Minimum Duty Cycle | 0.14 |
| 12 | Maximum Duty Cycle | 0.22 |
| 13 | Duty Cycle Resolution | 0.002 |

The MPC parameters were determined through an iterative tuning process to achieve accurate voltage tracking while maintaining fast transient response and stable steady-state operation. Higher weighting values were assigned to the overshoot penalty and voltage constraint terms to minimize voltage overshoot and ensure safe converter operation. The smoothness weight was introduced to avoid abrupt duty-cycle variations, thereby reducing switching oscillations and improving converter stability.

## 2.6. Simulation Scenarios

The performance of the proposed MPC-controlled Buck–Boost converter was evaluated through MATLAB/Simulink simulations under different operating conditions. The objective of the simulations was to investigate the voltage regulation capability of the converter under varying load conditions while maintaining a constant reference output voltage of 300 V. Two simulation scenarios were considered: (1) the Buck–Boost converter supplying resistive loads and (2) the Buck–Boost converter supplying a BLDC motor under different mechanical load torques.

- Simulation Scenario Buck Boost Converter

In the first simulation scenario, the Buck–Boost converter was evaluated using five different resistive loads of 150 Ω, 200 Ω, 300 Ω, 450 Ω, and 650 Ω. Throughout the simulations, the input voltage, converter parameters, switching frequency, and reference output voltage were kept constant, while only the load resistance was varied. This approach allows the effect of load variation on the converter performance to be systematically investigated. The corresponding simulation scenarios are summarized in Table 4.

Table 4. Simulation scenarios of the Buck–Boost converter

| No. | Load Resistance (Ω) | Units (Ω) |
|---|---|---|
| 1 | 150 | Ω |
| 2 | 200 | Ω |
| 3 | 300 | Ω |
| 4 | 450 | Ω |
| 5 | 650 | Ω |

For each loading condition, the output voltage, output current, output power, maximum and minimum output voltages, and maximum and minimum output currents were recorded. These measured parameters were subsequently used to calculate the voltage ripple and current ripple, which served as the primary indicators for evaluating the converter performance and voltage regulation capability

- Simulation Scenario of the MPC Based BLDC Motor Drive

After evaluating the Buck–Boost converter under resistive loading conditions, the proposed Model Predictive Control (MPC) was implemented to regulate the converter supplying the BLDC motor. The controller performance was evaluated under five different mechanical load torque conditions to investigate its capability in maintaining stable voltage regulation and motor operation. The applied load torque values are summarized in Table 5.

Table 5. Load torque scenarios of the BLDC motor drive

| No. | Load Torque (N.m) | Units (N.m) |
|---|---|---|
| 1 | 10 | N.m |
| 2 | 20 | N.m |
| 3 | 30 | N.m |
| 4 | 40 | N.m |
| 5 | 50 | N.m |

During each simulation, the output voltage reference was maintained at 300 V while the mechanical load torque was varied from 10 N·m to 50 N·m. Based on the prediction model and cost function, the MPC algorithm generated the optimal duty cycle for the Buck–Boost converter to ensure stable output voltage under varying operating conditions. Several electrical quantities were recorded during each simulation, including the output voltage, output current, output power, maximum and minimum output voltages, and maximum and minimum output currents. These measured parameters were used to calculate the voltage ripple and current ripple, which served as key indicators for evaluating converter stability and dynamic performance. In

addition, the BLDC motor performance was assessed through the stator current, rotor speed, electromagnetic torque, rise time, and settling time. The obtained results were subsequently analyzed to evaluate the effectiveness of the proposed MPC strategy under different loading conditions

## 3. RESULTS AND DISCUSSION

### 3.1. Simulation Buck Bost Converter without Controller

The initial simulation was carried out to evaluate the performance of the Buck–Boost converter without any control strategy. This simulation aims to investigate the inherent voltage regulation capability of the converter under different load resistance conditions before the implementation of the proposed Model Predictive Control (MPC). The simulation results are summarized in Table 6, while the corresponding output voltage, output current, and output power waveforms are illustrated in Figure 3.

Table 6. Simulation results of the Buck–Boost converter without controller

| No. | Load (Ω) | Vout (V) | Output Inductor Current (A) | Output Power (W) | Maximum Voltage (V) | Minimum Voltage (V) | Maximum Current (A) | Minimum Current (A) |
|---|---|---|---|---|---|---|---|---|
| 1 | 150 | 313 | 2.087 | 653 | 313 | 284 | 2.09 | 1.90 |
| 2 | 200 | 310 | 1.551 | 481 | 310 | 288 | 1.55 | 1.44 |
| 3 | 300 | 307 | 1.024 | 314 | 307 | 291 | 1.2 | 0.97 |
| 4 | 450 | 305 | 0.678 | 207 | 305 | 293 | 0.68 | 0.65 |
| 5 | 650 | 327 | 0.5 | 164 | 328 | 317 | 0.505 | 0.49 |

Figure 3 illustrates the output voltage, output current, and output power waveforms of the Buck–Boost converter operating without a controller under a load resistance of 200 Ω.

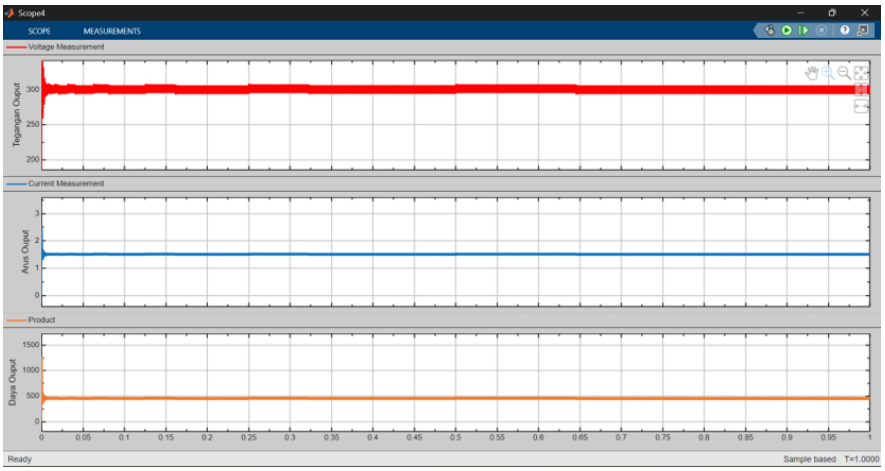



Figure 3. Output voltage, output current, and output power waveforms of the Buck–Boost converter without controller

The simulation results presented in Table 6 and Figure 3 demonstrate that the Buck–Boost converter operating without a controller is unable to maintain a constant output voltage under varying load resistance conditions. As the load resistance increases from 150 Ω to 650 Ω, the output current decreases from 2.087 A to 0.50 A, resulting in a corresponding reduction in output power from 653 W to 164 W. This behavior follows Ohm's law, where increasing the load resistance reduces the load current and consequently decreases the power delivered to the load.

The output voltage also varies between 305 V and 327 V, indicating insufficient voltage regulation under open-loop operation. Relative to the 300 V reference, the steady-state voltage error ranges from 1.67% to 9.00%, and the peak-to-peak output voltage ripple ranges from 3.41% to 9.72%, as quantified in Section 3.4. Since the converter operates with a fixed duty

cycle, it cannot compensate for disturbances caused by load variations, resulting in noticeable voltage deviations from the desired operating point. Moreover, the transient response shown in Figure 3 exhibits an initial overshoot before reaching steady-state operation. This overshoot occurs because no feedback mechanism is available to correct the converter output during transient conditions. These results indicate that the Buck–Boost converter without a control strategy has limited capability to regulate the output voltage and maintain stable operation under varying load conditions.

### 3.2. Performance of the MPC Based Buck Boost Converter

The performance of the proposed MPC-based Buck–Boost converter was evaluated under the same five resistive loads used in Section 3.1. The simulation was carried out using MATLAB/Simulink to evaluate the controller's ability to regulate the converter output voltage at the reference value of 300 V under different load conditions. The simulation results are summarized in Table 7, while the corresponding output voltage, output current, and output power responses are presented in Figure 4.

Table 7. Simulation results of the MPC-based Buck–Boost converter

| No. | Load (Ω) | Vout (V) | Output Current (A) | Output Power (W) | Maximum Voltage (V) | Minimum Voltage (V) | Maximum Current (A) | Minimum Current (A) |
|---|---|---|---|---|---|---|---|---|
| 1 | 150 | 314 | 2.099 | 660 | 314.85 | 314.45 | 2.0988 | 2.0964 |
| 2 | 200 | 314 | 1.575 | 495 | 314.95 | 314.65 | 1.5746 | 1.5732 |
| 3 | 300 | 315 | 1.05 | 330 | 315.02 | 314.82 | 1.0501 | 1.0494 |
| 4 | 450 | 315 | 0.7002 | 220 | 315.5 | 314.94 | 0.70020 | 0.69985 |
| 5 | 650 | 315 | 0.484 | 152 | 315.14 | 315.00 | 0.48484 | 0.48462 |

Figure 4 illustrates the output voltage, output current, and output power waveforms of the Buck–Boost converter with the proposed MPC under a load resistance of 200 Ω.

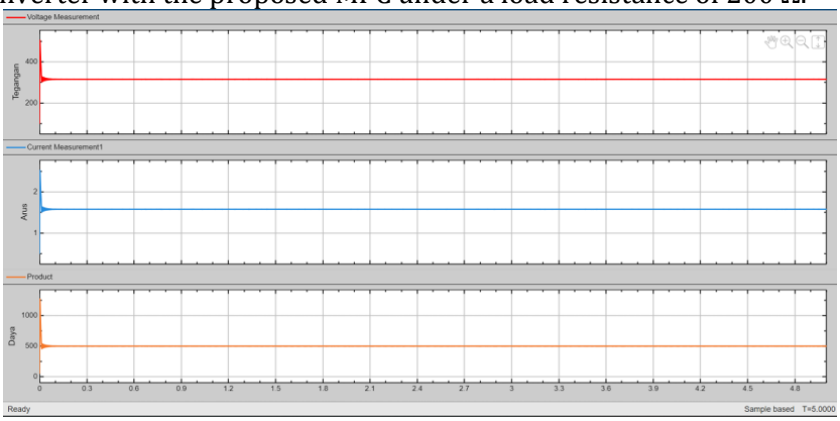



Figure 4. Output voltage, output current, and output power responses of the MPC-based Buck–Boost converter

The simulation results demonstrate that the implementation of the MPC significantly improves the voltage regulation capability of the Buck–Boost converter. Unlike the uncontrolled converter, the output voltage remains nearly constant at approximately 314–315 V despite variations in the load resistance, although it settles about 14–15 V above the 300 V reference. This improvement is achieved because the MPC predicts the future behavior of the converter using the system model and computes the optimal switching action at every sampling instant. As a result, the controller effectively compensates for load disturbances while maintaining stable converter operation.

As the load resistance increases, the output current decreases from 2.099 A to 0.484 A, leading to a reduction in output power from 660 W to 152 W. This trend is expected because a higher load resistance limits the current flowing through the load according to Ohm's law. However, unlike the uncontrolled converter, the output voltage remains stable, demonstrating that the MPC successfully decouples voltage regulation from load variations.

### 3.3. Performance of the MPC Based Motor Drive

The performance of the proposed MPC-based motor drive was assessed by integrating the Model Predictive Control (MPC) algorithm with the Buck–Boost converter supplying the BLDC motor. The simulation was performed using MATLAB/Simulink to evaluate the controller's ability to regulate the converter output voltage at the reference value of 300 V while maintaining stable motor operation under different load conditions. The corresponding simulation results are presented and discussed in the following subsections.

Table 8. Performance of the MPC-based BLDC motor drive under different load torque conditions

| No. | Load (N.m) | Output Voltage(V) | Stator Current(A) | Rotor Speed(rpm) | Electromagnetic Torque(N.m) | Rise Time(s) | Settling Time(s) |
|---|---|---|---|---|---|---|---|
| 1 | 10 | 356 | 5.961 | 1821 | 11.7 | 0.011 | 0.03 |
| 2 | 20 | 343 | 12.09 | 1368 | 18.5 | 0.02 | 0.03 |
| 3 | 30 | 339 | 18.13 | 1060 | 27.44 | 0.03 | 0.04 |
| 4 | 40 | 315 | 23.36 | 754.4 | 42.56 | 0.02 | 0.08 |
| 5 | 50 | 307 | 31.32 | 577 | 53.37 | 0.03 | 0.06 |

Figure 5 illustrates the dynamic responses of the MPC-based motor drive, including the output voltage, stator current, rotor speed, and electromagnetic torque under different load torque conditions.

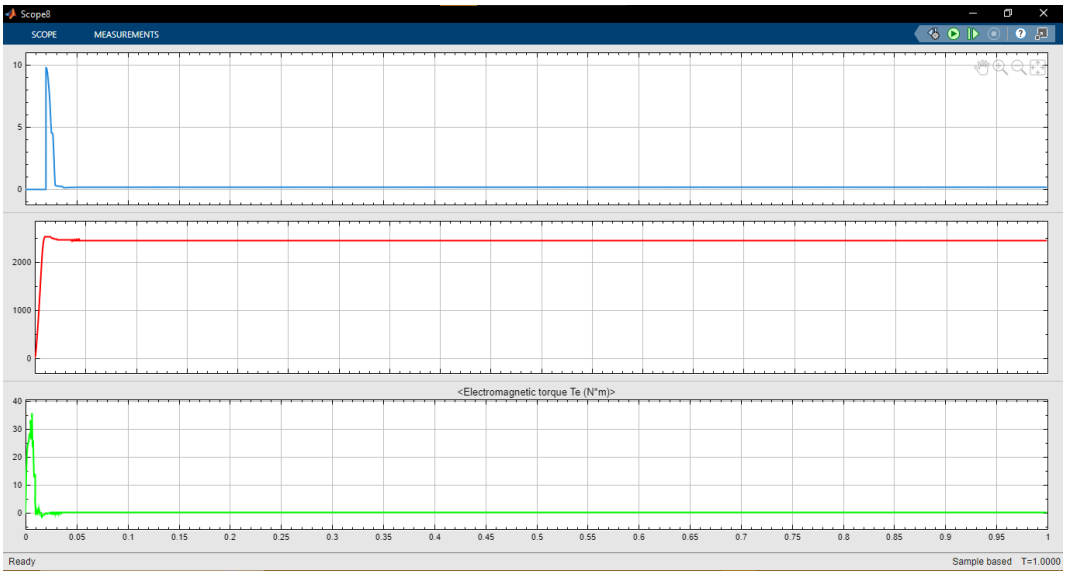



Figure 5. Output voltage, stator current, rotor speed, and electromagnetic torque responses of the MPC-based BLDC motor drive

The results presented in Table 8 and Figure 5 demonstrate that the proposed MPC-based motor drive maintains stable operation under different mechanical load torque conditions. As the load torque increases from 10 N·m to 50 N·m, the stator current increases from 5.961 A to 31.32 A. This increase occurs because a higher electromagnetic torque requires a larger stator current to satisfy the increased mechanical load, which is consistent with the operating principle of BLDC motor.

At the same time, the rotor speed decreases from 1821 rpm to 577 rpm as the mechanical load increases. This behavior is expected because the higher opposing torque demands more motor effort, reducing the rotor speed when the available electrical power is limited. Nevertheless, the MPC controller maintains the converter output voltage within the operating range of 307–356 V, which corresponds to a deviation of 2.33–18.67% from the 300 V reference, with the largest deviation at the lightest load (10 N·m), ensuring that sufficient electrical energy is continuously supplied to the motor despite the increasing load torque.

The electromagnetic torque increases proportionally with the applied mechanical load, indicating that the controller effectively adjusts the motor current to meet the required torque

demand. In addition, the recorded rise times of 0.011–0.030 s and settling times of 0.030–0.080 s demonstrate that the proposed controller provides a fast transient response and stable steady-state performance. These results confirm that the MPC not only improves converter voltage regulation but also enhances the dynamic performance and operational stability of the BLDC motor drive under varying load conditions.

### 3.4. Comparison Between the Uncontrolled and MPC-Based Buck–Boost Converter

To verify the effectiveness of the proposed controller, the uncontrolled and the MPC-based converters were compared under the same five resistive loads (Tables 6 and 7). The steady-state voltage error relative to the 300 V reference, the output voltage ripple, and the inductor (output) current ripple were calculated as follows:

$$e_{\mathrm{V}} = \frac{|V_{\mathrm{out}} - V_{\mathrm{ref}}|}{V_{\mathrm{ref}}} \times 100\% \quad (14)$$

$$\Delta V = \frac{V_{\max} - V_{\min}}{(V_{\max} + V_{\min})/2} \times 100\% \quad (15)$$

$$\Delta I = \frac{I_{\max} - I_{\min}}{(I_{\max} + I_{\min})/2} \times 100\% \quad (16)$$

where $V_{\mathrm{ref}}$ = 300 V is the reference voltage, $V_{\mathrm{out}}$ is the steady-state output voltage, $V_{\max}$ and $V_{\min}$ are the maximum and minimum output voltages, and $I_{\max}$ and $I_{\min}$ are the maximum and minimum currents recorded in Tables 6 and 7. The results are presented in Table 9.

Table 9. Comparison of voltage error and ripple between the uncontrolled and MPC-based converter

| Load (Ω) | Without controller | | | MPC | | |
|---|---|---|---|---|---|---|
| | $e_V$ (%) | ΔV (%) | ΔI (%) | $e_V$ (%) | ΔV (%) | ΔI (%) |
| 150 | 4.33 | 9.72 | 9.52 | 4.67 | 0.127 | 0.114 |
| 200 | 3.33 | 7.36 | 7.36 | 4.67 | 0.095 | 0.089 |
| 300 | 2.33 | 5.35 | 21.20 | 5.00 | 0.064 | 0.067 |
| 450 | 1.67 | 4.01 | 4.51 | 5.00 | 0.178 | 0.050 |
| 650 | 9.00 | 3.41 | 3.02 | 5.00 | 0.044 | 0.045 |

Table 9 shows that the proposed MPC reduces the output voltage ripple from 3.41–9.72% to 0.044–0.178% and the current ripple from 3.02–21.20% to 0.045–0.114%, i.e., by one to two orders of magnitude for every load. The peak-to-peak voltage variation decreases from 11–29 V to 0.14–0.56 V, and the steady-state output voltage changes by only 1 V (314–315 V) over the whole load range, compared with 22 V (305–327 V) without the controller. These results confirm that the MPC effectively rejects load disturbances. However, the MPC-based converter exhibits a nearly constant steady-state error of 4.67–5.00% because the output voltage settles at 314–315 V instead of 300 V; at 300 Ω and 450 Ω, this error is even larger than that of the uncontrolled converter. Since the error is almost independent of the load, it indicates an offset in the reference tracking of the controller, which may be reduced by adjusting the tracking weight and integral gain listed in Table 3. Therefore, the effectiveness of the proposed MPC lies mainly in its ripple suppression and load-independent voltage regulation, whereas the accuracy of reference tracking still needs to be improved.

## 4. CONCLUSION

The simulation results demonstrate that the proposed Model Predictive Control (MPC) effectively improves the performance of the Buck–Boost converter. Compared with the uncontrolled converter under the same resistive loads, the MPC reduced the output voltage ripple from 3.41–9.72% to 0.044–0.178% and the inductor current ripple to below 0.12%, and kept the output voltage within 314–315 V over the entire load range, whereas the uncontrolled converter varied between 305 V and 327 V. However, a nearly constant steady-state error of 4.67–5.00% relative to the 300 V reference remained.

In the BLDC motor drive, the controller provided a fast transient response with rise times of 0.011–0.030 s and settling times of 0.030–0.080 s. As the mechanical load increased from 10 N·m to 50 N·m, the stator current increased from 5.961 A to 31.32 A and the electromagnetic torque from 11.7 N·m to 53.37 N·m, while the rotor speed decreased from 1821

rpm to 577 rpm, which is consistent with the operating principle of the BLDC motor. These results demonstrate that the proposed controller maintains stable motor operation over a wide operating range.

Despite the satisfactory overall performance, several limitations were identified. The output voltage of the motor drive varied from 356 V at 10 N·m to 307 V at 50 N·m, corresponding to deviations of 18.67% and 2.33% from the reference, which indicates that voltage regulation under light mechanical loads is still insufficient. In addition, startup overshoot was still observed, suggesting that the prediction horizon, control horizon, and weighting factors have not yet been fully optimized. Therefore, future work should focus on improving the MPC tuning strategy to eliminate the steady-state voltage offset, incorporating adaptive or robust MPC techniques, comparing the proposed controller with alternative controllers such as PI or PID, and validating it through hardware implementation.

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