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Position Control of A Permanent Magnet Brushless DC Motor using A Model Predictive Control Method with Laguerre Functions

Abstract: **-** This article focuses on reducing the high computational load in the MPC method with long prediction horizons, by using orthogonal basis functions (Laguerre functions) for controlling the position of a BLDC motor. MPC is one of the controllers that can be used to achieve the desired and optimal dynamics of the BLDC motor. One of the main challenges in the practical implementation of MPC, which limits its application, is the computational volume, especially with high prediction horizons. In fast systems and systems with complex dynamics and small sampling times, the computational load increases exponentially, which leads to a decrease in real-time execution speed and requires shorter prediction horizons. This high computational load can be approximated using discrete orthogonal basis functions, such as Laguerre polynomials. The main advantage of this approach is the optimization of coefficients with fewer Laguerre functions instead of optimizing the control trajectory itself, making it possible to choose a longer prediction horizon. Simulation and implementation result clearly demonstrate that the Laguerre-based MPC method benefits from reduced computation time, indicating a significant reduction in computational load.

Keywords: BLDC motor, predictive control, Laguerre functions

1. INTRODUCTION

Brushless DC motors (BLDC) have gained significant attention over the past two decades due to their numerous advantages, such as high efficiency, wide speed range, flat torque-speed characteristics, high reliability, and low maintenance costs. They are utilized in various applications, including aerospace, industrial automation, medical devices, and automotive industries [1]. However, the complex and nonlinear behavior of these motors presents a substantial challenge in designing an effective controller that can provide accurate and stable responses under all dynamic conditions. One critical factor affecting the performance of synchronous motors is the optimal design of the controller [2]. Various control methods for permanent magnet motors are illustrated in Figure 1. For successful position control and tracking, time-varying or nonlinear controllers are employed. In linear control methods, applying linear control to a nonlinear system does not yield satisfactory performance across the entire dynamic range. Due to dependence on model parameters, it requires adjustments and retuning of control parameters. Furthermore, linear control performs poorly under disturbances and load variations and exhibits slow frequency response at high speeds, making it unsuitable for nonlinear systems. In sliding mode control, high switching frequency limitations and the presence of uncertainties can cause the system states to oscillate around the sliding surface, leading to instability [3]. In intelligent control methods, accumulated errors at each processing stage can result in persistent errors at the system output, necessitating the use of an error compensator, which, in turn, increases computational load [4].

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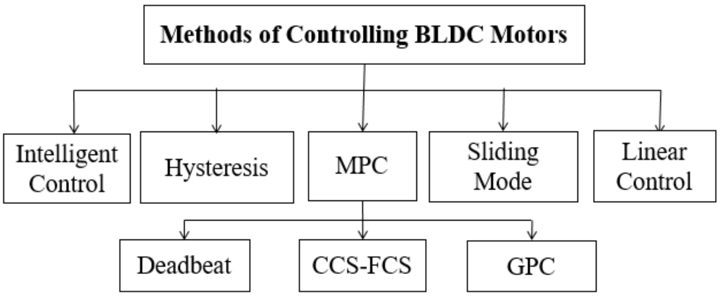


Figure 1: Control Methods for Permanent Magnet Motors

In hysteresis control methods, the absence of a modulator leads to variable switching frequencies, which can increase system losses [5]. The Deadbeat method, a type of predictive control, maintains a constant switching frequency through the use of a modulator and can be applied to unconstrained systems. In Generalized Predictive Control (GPC), the optimization problem is solved offline and is applicable to both linear and unconstrained systems. Model Predictive Control (Model Predictive Control - MPC), particularly continuous predictive control, offers advantages such as applicability in unstable and nonlinear systems with multiple variables and constraints, as well as utilizing feedback mechanisms to compensate for predictive errors and manage dead times, making it superior to previous methods [6]. Given the nonlinear dynamics of these motors and variations in load and speed, precise control necessitates the use of advanced control methods capable of predicting these changes and effectively achieving optimal settings. Continuous predictive control, as one of the most advanced control methods for dynamic systems, can provide accurate predictions of future motor behavior using a mathematical model of the system and compute control inputs to achieve optimal and rapid responses [7]. Additionally, the use of Laguerre functions as orthogonal basis functions in modeling and controlling nonlinear systems can significantly enhance the accuracy of the model and controller performance. Laguerre basis functions are a set of polynomial functions particularly useful in optimization problems. These functions are designed as orthogonal functions in functional space, making them beneficial for many mathematical issues requiring function analysis or approximation. Laguerre functions are specifically introduced in the form of high-order polynomials that exhibit zero overlap properties with other functions. These features are particularly effective in solving differential equations, modeling dynamic systems, and optimization problems. In summary, BLDC motors are a category of synchronous electric motors where the magnetic field is produced by permanent magnets. These motors have a longer lifespan and higher efficiency due to the absence of brushes [8]. Control of these motors typically utilizes traditional methods such as vector control or direct field control. However, these methods do not provide satisfactory responses for complex and nonlinear systems like BLDC motors. Therefore, the use of model predictive control (MPC), especially continuous predictive control, has emerged as an effective approach to enhance performance and increase the stability of dynamic systems. In this context, employing orthogonal basis functions like Laguerre functions for modeling systems, particularly for BLDC motors, effectively reduces the nonlinear complexities of the system and improves prediction accuracy [9]. The primary objective of this article is to design and implement a continuous predictive controller for BLDC motors using Laguerre functions as modeling tools. This study aims to significantly improve the dynamic response of BLDC motors by utilizing more accurate models and precise predictions of system behavior. Specifically, the aim of this research is to design a control system that is capable of providing optimal performance and high stability under various operating conditions, including sudden changes in load or speed. This paper attempts to address these challenges by introducing and analyzing novel predictive control methods based on models and Laguerre functions. The steps presented in this paper are as follows:

In the introduction section discusses the advantages of BLDC motors, their control methods, and their applications, while also introducing ideas and strategies for reducing computational load. Sections 2 and 3 outline the operating principles and mathematical model, as well as the D-Q reference frame of BLDC motors. Section 4 presents the model predictive control method for BLDC motors. Section 5 elaborates on the proposal to use Laguerre functions, detailing the subject and the relationships utilized. Finally, Section 6 describes and compares the simulation and implementation results.

2. Operating Principles of BLDC Motors

BLDC motors, also known as brushless DC motors or electronically controlled electric motors, are among the most widely used electric motors across various industries. These motors are favored for their high efficiency, long lifespan, precise speed and torque control, and low maintenance requirements, making them suitable for applications such as electric vehicles, HVAC systems, motion systems, and even household appliances. Like other electric motors, BLDC motors utilize magnetic force to generate motion; however, the main difference is that BLDC motors replace brushes and commutators with electronic circuits. This feature results in BLDC motors having higher efficiency and longer lifespans compared to conventional DC motors. In BLDC motors, an electronic control system applies current to the windings to create a rotating magnetic field in the stator, which drives the rotor [1]. This operation is guided by rotor position sensitivity, typically achieved through Hall sensors or sensorless control. The waveform of the back EMF voltage, current, and Hall effect sensors for the phases of the BLDC motor is shown in Figure 2.

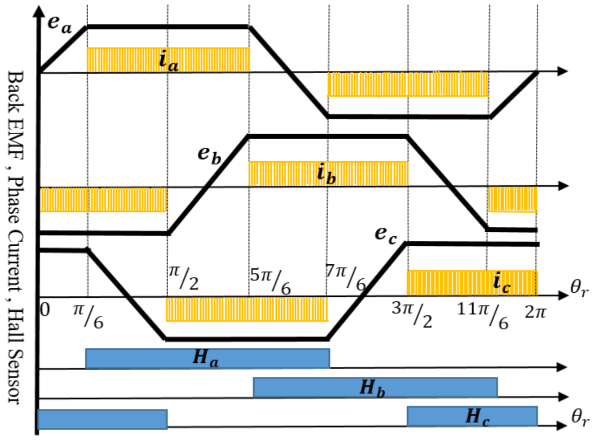


Figure 2: Waveform of Back EMF Voltage, Current, The phase voltageand Hall Effect Sensors for BLDC Motor Phases

The governing equations for the operation of a BLDC motor typically include equations for torque, current, voltage, and motor speed [7].

Equation 1, the voltage equation for the BLDC motor is given by:

$$V_a = Ri_a + L\frac{d_t}{d_i}i_a + e_a \quad (1)$$

The phase voltage equations can be rewritten as follows:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & L_{ab} & L_{ac} \\ L_{ba} & L & L_{bc} \\ L_{ca} & L_{cb} & L \end{bmatrix} . \frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2)$$

where v_a, v_b, v_c represents the phase voltages, i_a, i_b, i_c represents the phase currents, e_a, e_b, e_c is the back EMF of the motor phase, R is the phase resistance, and L is the inductance between the phases. The motion equation is expressed as follows:

$$\frac{d}{dt}\omega_r = \frac{(T_e - T_l - B\omega_r)}{J} \quad (3)$$

where B is the damping constant, J is the internal drive torque, and T_l is the load torque. Equation 4 the equation for the torque produced by the BLDC motor is:

$$T = k_t i_a \quad (4)$$

where T is the generated torque, k_t is the torque constant (dependent on motor and rotor characteristics), and i_a the current in the windings is equation 5 of the BLDC motor speed equation:

$$\omega = \frac{1}{j}(T - T_l) \quad (5)$$

where ω is the rotor speed, J is the moment of inertia, and T_l is the load torque. The motion equation can be rewritten as follows:

$$\frac{d}{dt}\omega_r = \frac{(T_e - T_l - B\omega_r)}{J} \quad (6)$$

where B is the damping constant, J is the internal drive torque, and T_l is the load torque. Equation 7 the equation for the back electromotive force (Back EMF) of the BLDC motor is:

$$e_a = k_e \omega \quad (7)$$

where e_a is the back EMF, k_e is the back EMF constant, and ω is the rotor speed.

3. Modeling of BLDC Motor in the D-Q Reference Frame

In control methods, the abc reference frame is unsuitable because the voltages and currents of the motor are oscillatory even at constant speed and load. This makes its use in formulating suitable control laws inappropriate. In the D-Q reference frame, the voltages and currents are constant for fixed speed and torque. Therefore, by using the Clarke and Park transformations, the abc reference frame is converted to the D-Q reference frame [10]. In the D-Q reference frame, the equations will be as follows:

$$V_d = Ri_d + L\frac{di_d}{dt} + \omega L i_q + E_d \quad (8)$$

$$V_q = Ri_q + L\frac{di_q}{dt} + \omega L i_d + E_q \quad (9)$$

It is important to note that in the modeling, to compensate for the nonlinear effects in the proposed model, the nonlinear factors are assumed to be measurable disturbances and have been added to the model.

4. Continuous Predictive Control

Continuous predictive control is one of the advanced methods in the field of controlling dynamic systems, aiming to predict the future states of the system and adjust inputs in a way that optimizes system performance. Unlike discrete control methods, where inputs are applied to the system at specific times, continuous predictive control continuously calculates and applies inputs. This type of control is particularly useful for complex, nonlinear systems with time-varying behaviors. Continuous predictive control involves using mathematical models of the system to predict its future behavior over time. These predictions are made over a specified time horizon, and inputs are adjusted to minimize costs over time. Optimization algorithms are employed to calculate optimal inputs at each moment. The continuous state-space model of the motor is transformed into its discrete equivalent based on the Euler process transformation. However, a small sampling time is used to maintain the accuracy of the model [11].

The discrete state-space model of the system is obtained as follows:

$$\begin{bmatrix} \Delta x_m(k+1) \\ y(k+1) \end{bmatrix} = \begin{bmatrix} A_m & o_m^T \\ C_m A_m & I_{q\times q} \end{bmatrix} \begin{bmatrix} \Delta x_m(k) \\ y(k) \end{bmatrix} + \begin{bmatrix} B_m \\ C_m B_m \end{bmatrix} \Delta u(k) \quad (10)$$

$$y(k) = \begin{bmatrix} o_m & I_{q\times q} \end{bmatrix} \begin{bmatrix} \Delta x_m(k) \\ y(k) \end{bmatrix}$$

Additionally, in the above relations, q represents the number of outputs, and o_m is a zero matrix of appropriate dimensions. For simplification, equation (10) is rewritten as:

$$\begin{aligned} x(k+1) &= Ax(k) + B\Delta u(k) \\ y(k) &= Cx(k) \end{aligned} \qquad (11)$$

Based on the state-space model (C, B, A), the prediction of state variables from the moment of sampling k_i, within a limited prediction horizon N_p, can be solved from the above equation. The prediction of state variables in $k_i + N_p$ can be expressed as follows:

$$x(k_i + N_p \mid k_i) = A^{N_p} x(k_i) + \sum_{i=0}^{N_c-1} A^{N_p-i-1} B\Delta u(k_i+1) \qquad (12)$$

$$y(k_i + N_p \mid k_i) = CA^{N_p} x(k_i) + \sum_{i=0}^{N_c-1} CA^{N_p-i-1} B\Delta u(k_i+1) \qquad (13)$$

The vectors Y and ΔU can be obtained as follows:

$$\Delta\text{U}= \left[\Delta u(k_i)^T \, \Delta u(k_i+1) ... \Delta u(k_i+N_c-1)^T \right]^T \qquad (14)$$

$$Y = \left[y(k_i+1 \middle| k_i)^T \, y(k_i+2 \middle| k_i)^T ... y(k_i+N_p \middle| k_i)^T \right] \qquad (15)$$

The output Y can be expressed as:

$$Y = Fx(k_i) + \phi\Delta U \qquad (16)$$

where:

$$F = \begin{bmatrix} CA & CA^2 & CA^3 & ... & CA^{N_p} \end{bmatrix}^T$$

$$\phi = \begin{bmatrix} CB & 0 & \cdots & 0 \\ CAB & CB & \cdots & 0 \\ CA^2B & CAB & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ CA^{N_p-1}B & CA^{N_p-2}B & \cdots & CA^{N_p-N_c}B \end{bmatrix}$$

In systems with small sampling times or complex system dynamics, the computational load is correspondingly high. It is proposed to use the expansion of discrete orthogonal polynomials to approximate and reduce computational load.

5. Laguerre Orthogonal Basis Functions

In nonlinear systems or systems where accurate modeling is challenging, the use of Laguerre orthogonal basis functions can help simplify models and the optimization process. These functions can be used to approximate nonlinear models or models of complex systems. In nonlinear control problems, Laguerre orthogonal basis functions can be utilized to approximate dynamic equations and transition systems from complex states to solvable or optimized states. In continuous predictive control problems, especially under conditions where the system has complex and nonlinear dynamics, the use of Laguerre orthogonal basis functions in optimization can be beneficial. Since Laguerre functions form a set of orthogonal functions, they can be incorporated into optimization problems where analysis of the objective function and constraints is required. Additionally, in systems modeled as nonlinear, the use of Laguerre basis functions can effectively simplify and enhance the accuracy of the optimization process. These functions are effective in optimizing inputs and improving the performance of continuous predictive control. Given that any continuous function can be expressed in terms of an expansion of orthogonal functions, any control input signal can be represented as the impulse response of a stable system, and each impulse response of a stable system can be approximated using Laguerre functions [13]. The changes in the control signal, in terms of impulse functions, can be obtained as follows:

$$\Delta u(k_i + i) = [\delta(i)\delta(i-1)...\delta(i-N_c+1)]\Delta U \quad (17)$$

Now, the Laguerre functions are recursively defined as follows:

$$\Gamma_k(z) = \Gamma_{k-1}(z)\frac{z^{-1}-a}{1-az^{-1}} \quad (18)$$

$$\Gamma_1 = \frac{\sqrt{1-a^2}}{1-az^{-1}} \quad (19)$$

To reduce steady-state error, the discrete dynamics of the system with output can be expressed as follows [16]. The time form of Laguerre functions used in the above equations is as follows:

$$\Delta u(k_i + k) = \sum_{j=1}^{N} c_j(k_i) l_j(k) = L(k)^T \eta \quad (20)$$

where:

$$L(k) = [l_1(k) l_2(k) ... l_N(k)]^T$$
$$\eta = [c_1 \quad c_2 \quad ... \quad c_N]^T$$
$$c_j = 1, 2, ..., N$$

The Laguerre functions are recursively obtained as follows:

$$L(k+1) = A_l L(k) \quad (21)$$

where:

$$A_l = \begin{bmatrix} a & 0 & 0 & 0 & 0 \\ \beta & a & 0 & 0 & 0 \\ -a\beta & \beta & a & 0 & 0 \\ a^2\beta & -a\beta & \beta & a & 0 \\ -a^3\beta & a^2\beta & -a\beta & \beta & a \end{bmatrix}$$

$$L(0) = \sqrt{\beta}\begin{bmatrix} 1 & -a & a^2 & -a^3 & \cdots & (-1)^{N-1}a^{n-1} \end{bmatrix}$$

In these functions, $\beta = 1 - a^2$ and $0 \geq > a \ 1$ is the pole of the discrete Laguerre network, and the prediction of state variables for multi-input, multi-output systems is given by:

$$x(k_i + N_p | k_i) = A^{N_p} x(ki) + \sum_{i=0}^{N_p} A^{N_p - i - 1}[B_1 L_1(i) + B_2 L_2(i) + \cdots + B_m L_m(i)]\eta_p \quad (22)$$

where:

$$\eta_p^T = \begin{bmatrix} \eta_1^T & \eta_2^T & \cdots & \eta_m^T \end{bmatrix}$$

B_1 to B_m represents: (i-the number of columns of matrix B).

Thus, the variable being optimized is the coefficients of the Laguerre functions. Then, by defining i_d^* and i_q^* as the reference currents in the D-Q frame, the state variables are rewritten as follows:

$$\hat{x}(k) = [i_d(k) - i_d(K-1), i_q(k) - i_q(K-1), \\ i_d(k) - i_d^*, i_q(k) - i_q^*]^T \tag{23}$$

Therefore, the cost function can be expressed as follows:

$$j = \sum_{j=1}^{N_p} \hat{x}(k_i + j \left| k_i \right)^T Q_\alpha \hat{x}(k_i + j \left| k_i \right) + \eta_p^T R_\alpha \eta_p \tag{24}$$

where:

$R_\alpha = \gamma^2 R$ and $Q_\alpha = \gamma^2 Q + (1-\gamma^2) P_\infty$ and P_∞ are obtained from solving the algebraic Riccati equation. By optimizing relation (32), the optimal cost function is rewritten as follows:

$$J = \eta_p^T \Omega \eta_p + 2\eta_p^T \psi \hat{x}(k_i) + \Gamma \tag{25}$$

where:

$$\Omega = \sum_{m=1}^{N_p} \phi(m) Q_\alpha \phi(m)^T + R_\alpha$$

$$\psi = \sum_{m=1}^{N_p} \phi(m) Q_\alpha \hat{A}^m$$

$$\Gamma = \sum_{m=1}^{N_p} \hat{x}(k_i)^T (\hat{A}^T)^m Q_\alpha \hat{A}^m \hat{x}(k_i)$$

$$\phi(m) = \sum_{i=1}^{N_{p-1}} \hat{A}^{N_p - i - 1} [\hat{B}_1 L_1(i) + \hat{B}_2 L_2(i)]$$

$$\eta_p^T = [\eta_1^T \quad \eta_2^T]$$

Also, is $\hat{A} = \frac{A}{\alpha}$ and $\hat{B} = \frac{B}{\alpha}$ and $Q_\alpha \geq 0$ and $R_\alpha \rangle 0$.

By minimizing η under the above cost function, the problem can be solved.

6. Simulation and Results Obtained

The aim of this paper is to simulate and implement BLDC motor control using model predictive control methods with Laguerre functions. In this approach, a significant reduction in computational load in model predictive control is expected by approximating computations with one of the discrete orthogonal basis functions known as Laguerre polynomials. Therefore, this paper conducts simulations in two scenarios: model predictive control without using Laguerre functions and model predictive control with Laguerre functions, comparing the results. It is worth mentioning that all experimental conditions in both scenarios are equal, with a sampling frequency of 10 kHz. Additionally, in both scenarios, two prediction horizons of 4 and 40 and control horizons of 1 and 20 are considered, along with a disturbance load of 0.5 Nm. The only difference between the two scenarios is the control program algorithm. Table 1 shows the specifications and components of the BLDC motor used in the simulation.

Table 1: Parameters of BLDC Motor

J	0.07 Kgm^2
L	0.005H
R	3.25Ω
B_v	1.1×10^{-4}Nm.s
Ψ	0.122Wb
P_n	4

Based on the aforementioned information, the block diagram of the continuous model predictive control system (CCS-MPC) is shown in Figure (3). A PWM modulator is responsible for converting the control signals obtained from model predictive control into control signals for the three-phase inverter. Engineering transformations Clark and Park are also utilized in the simulation. Hall effect sensors and potentiometers are used to determine and detect the rotor position and provide feedback to the controller.

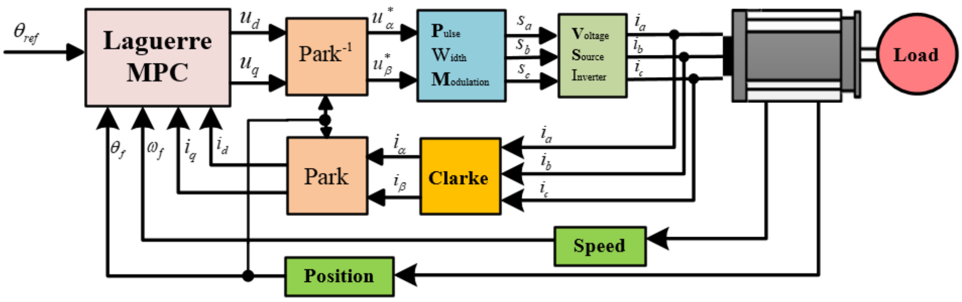


Figure (3): Block Diagram of BLDC Motor Control System

In the first part of the simulation, a prediction horizon of 4 and a control horizon of 2 are used in the algorithm. As shown in Figure (4), due to the use of lower control horizons, the tracking error of 0.02 relative to the reference signal is well maintained. Figure (5) also shows the phase currents signals and back EMF voltages.

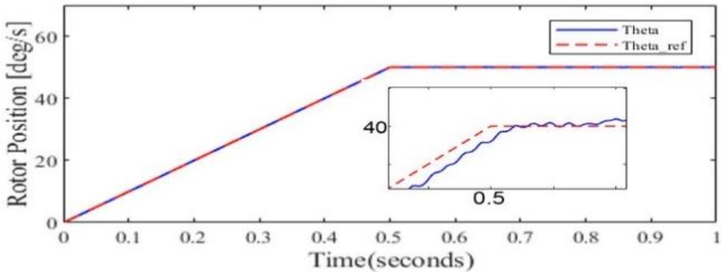


Figure (4): Reference Position Signal and Tracking Signal

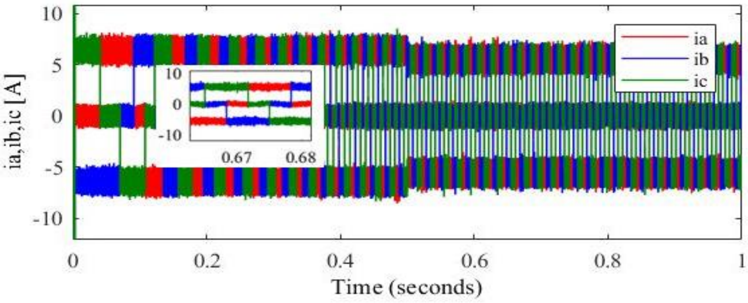


Figure (5): Phase Currents a, b, c

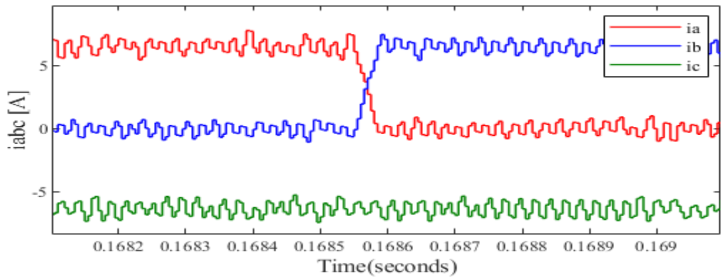


Figure (6): Commutation Moment of Phase Currents a, b, c

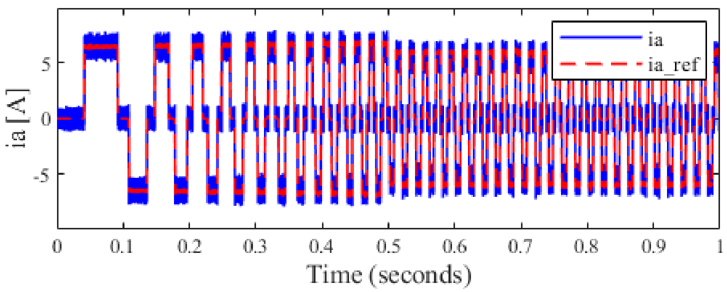


Figure (7): Phase a Current Along with Reference Current

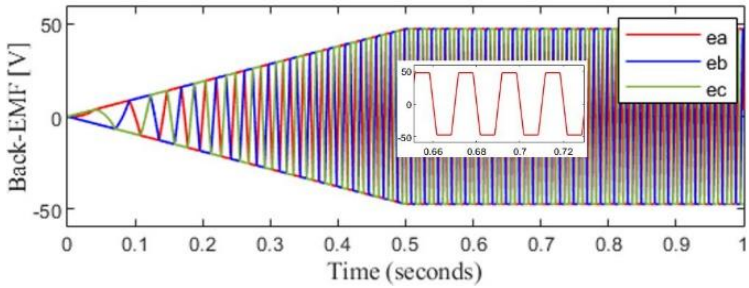


Figure (8): Back-EMF Voltage of Phases a, b, c

In the next section, the simulation of the model predictive control approach using Laguerre functions and without using Laguerre functions is addressed with a prediction horizon of 40 and a control horizon of 20, using a sinusoidal reference position signal with a frequency of 10 Hz, and the results are compared.

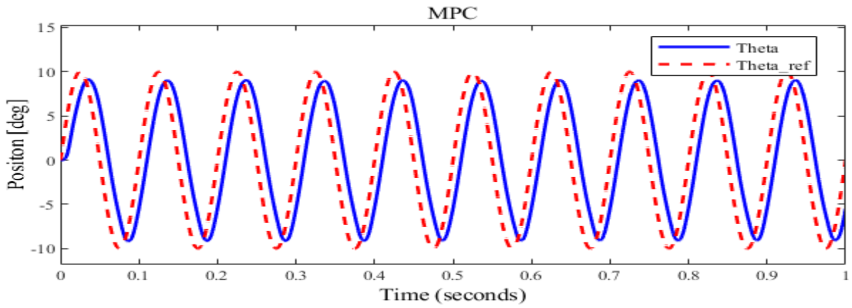


Figure (9): Position Control Using Predictive Method Without Laguerre Functions (np=40, nc=20)

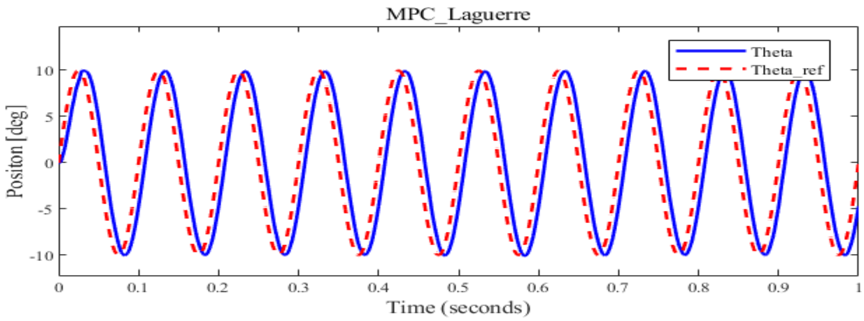


Figure (10): Position Control Using Predictive Method With Laguerre Functions (np=40, nc=20)

The goal of the proposed control system is to accurately track the reference signal in the high prediction and control horizons. As observed, the tracking error using Laguerre functions is lower than that of the system without Laguerre functions. However, since the computations in the simulation are not real-time, this difference will be more pronounced in the implementation, to the extent that the system becomes unstable and tracking the reference signal becomes impossible. The time spent processing information on the computer system, as specified in the table, is 1800 seconds for the simulation of the system without using Laguerre functions and 130 seconds for the system using Laguerre functions, indicating an estimation and reduction in computational load without sacrificing accuracy in tracking the reference signal. A comparison of the responses of both controllers in position tracking shows that tracking by the Laguerre-based MPC algorithm is significantly better than that of conventional MPC.

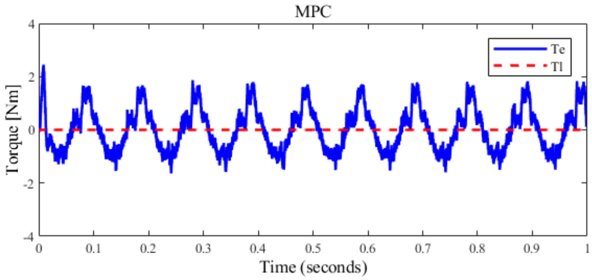


Figure (11): Torque Waveform of BLDC Motor Using Predictive Control Without Laguerre Functions (np=40, nc=20)

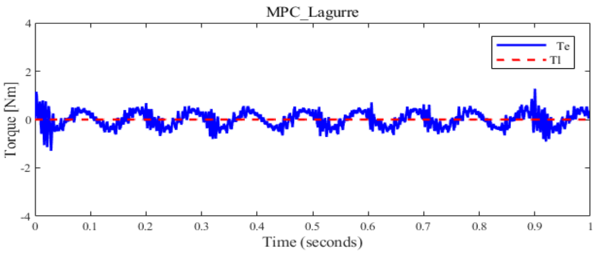
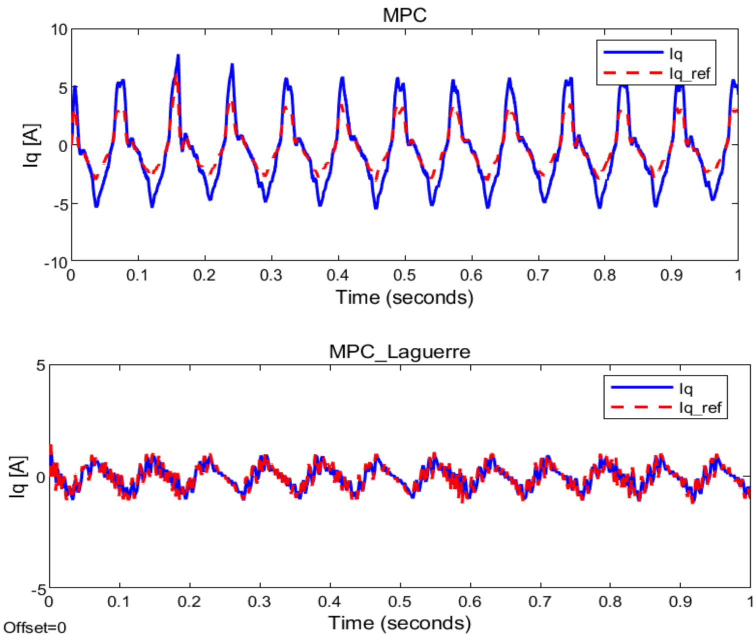


Figure (12): Torque Waveform of BLDC Motor Using Predictive Control With Laguerre Functions (np=40, nc=20)

In Figures (11) and (12), the torque waveform of the BLDC motor is displayed using predictive control without Laguerre functions and with Laguerre functions. The ripple torque in the case without using Laguerre functions is 1.6 Nm, while in the Laguerre-based case, it is 0.8 Nm. Additionally, the waveforms obtained from the two current components i_d and i_q for both cases (without Laguerre functions and with Laguerre functions) are shown in Figure (13). As can be seen, in the predictive control method using Laguerre functions, the currents i_d and i_q have significantly decreased. Generally, the closer i_d is to zero, the lower the noise will be.



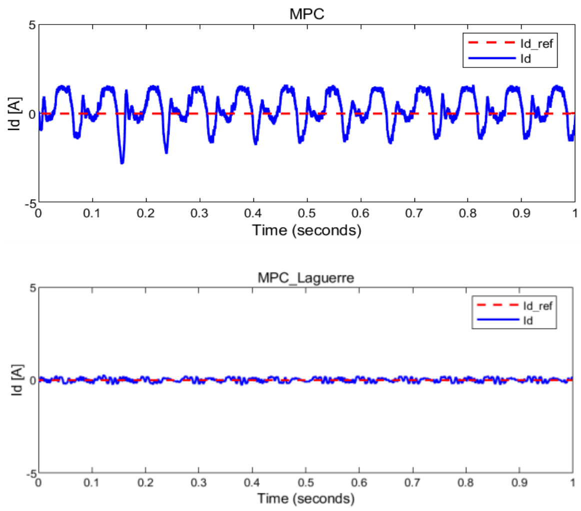


Figure (13): Waveforms of Currents iq and id Using Predictive Control Without Laguerre Functions and With Laguerre Functions

In Figures (14) and (15), the THD and harmonic distortion values in both scenarios are shown. In the predictive control case without using Laguerre functions, the THD is 81% and the harmonic distortion is 22.9. In the predictive control case using Laguerre functions, the THD is 77% and the harmonic distortion is 22.7, indicating a reduction of 0.04% in THD and 0.2 in harmonic distortion.

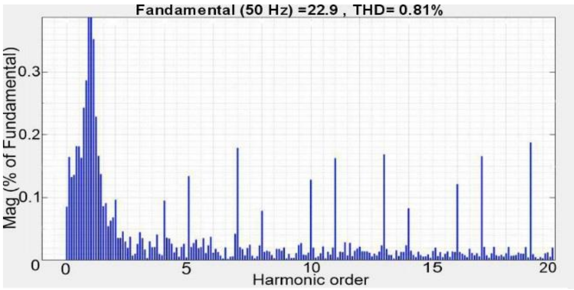


Figure (14): THD and Harmonic Distortion of MPC Without Using Laguerre Functions

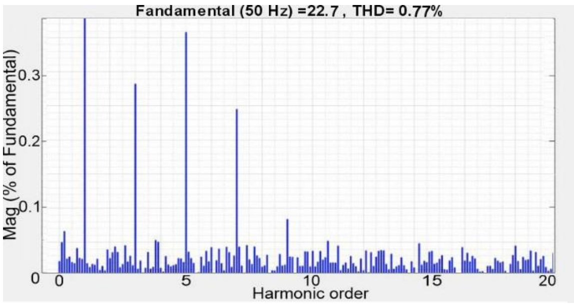


Figure (15): THD and Harmonic Distortion of MPC With Using Laguerre Functions

Table 2: Online Computation Time

Test Component		Processing Time(s)	Torque Ripple (Nm)	THD (%)	FFT
Np = 40 Nc = 20	MPC	1800	1.6	0.81	22.9
	LMPC	130	0.8	0.77	22.7
Computer Used :Intel(R) Core(TM) i7-4600 CPU @2.10GHZ					

In the implementation section, as shown in Figures 16 and 17, the hardware consists of the following parts:

1. Processor, utilizing an ARM processor and STM32 microcontroller, with an RS-422 serial port for communication with the computer.

2. Driver, composed of a three-phase half-bridge driver for the BLDC motor using N-channel MOSFETs.

3. Power Supply, responsible for powering the processor, driver, and sensors.

4. BLDC Motor, with specifications mentioned in Table 1, along with three Hall effect sensors.

5. Gearbox, with a conversion ratio of 1 to 16.

6. Potentiometer, for rotor position feedback to the processor.

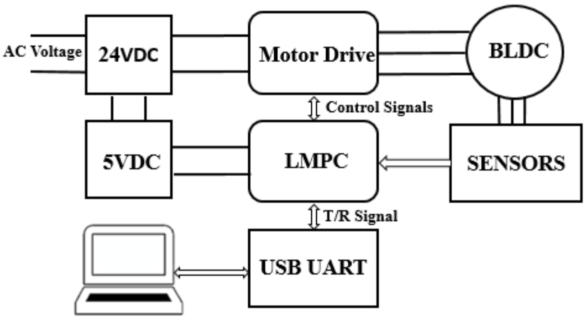


Figure 16: Hardware System

Now, this section will focus on the implementation and examination of its results. Figure 18 shows a view of the proposed hardware system.

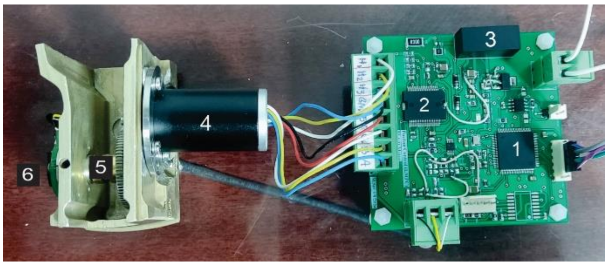


Figure 17: Proposed Hardware System

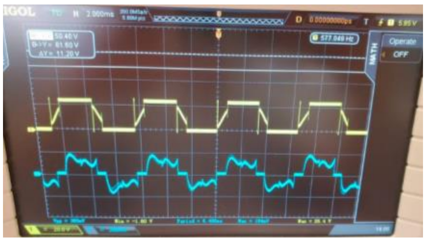


Figure 18

Channel 1: Voltage Back EMF to Phase A

Channel 2: Current to Phase A

In the implementation of the proposed algorithm, the Voltage Back EMF for Phase A and the current signal for Phase A are shown in Figure 18. Some ripple in the current has occurred, likely due to the mismatch between the trapezoidal waveform and the motor's Back EMF profile, which is natural in systems using trapezoidal commutation.

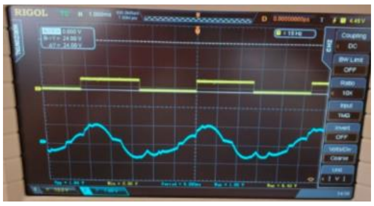


Figure 19

Channel 1: Hall A

Channel 2: Voltage Ao

Figure 19 shows the waveform of Hall sensor 1. In BLDC motors, phase displacement cannot occur without changing the Hall signals. Hall sensors are specifically designed to align phase switching with rotor position. If the phases do not switch correctly in sync with the Hall signals, it can cause the motor torque to change in the wrong direction, leading to conflicts within the motor, which naturally increases current and, consequently, current limits and heating of the system.

CONCLUSION

In this paper, to improve the performance of MPC in long time horizons for the position control of Permanent Magnet Synchronous Motors (BLDC), an MPC algorithm utilizing Laguerre functions was proposed. The above algorithm was then simulated and practically implemented. Simulation results show that the Laguerre-based MPC method benefits from reduced computational time, indicating a decrease in computational load. This method also demonstrates tracking of the reference under both steady and dynamic conditions for the BLDC motor. Practical implementation results support this finding. A notable aspect of this method is the number of parameters required for precise operation in BLDC motor control. These parameters have been empirically tuned, and further research is needed to determine the parameters for the proposed CCS-MPC. Future research could lead toward sensorless operations for the proposed design, which will be explored in subsequent studies.

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