

PERFORMANCE COMPARISON OF MODEL PREDICTIVE CONTROL (MPC) AND NONLINEAR PID (NPID) FOR BLDC MOTOR SPEED CONTROL

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ABSTRACT

The utilization of Brushless Direct Current (BLDC) motor in real world is undoubtedly growing because of their high efficiency, low maintenance requirements, minimal noise level, and reliability. Nevertheless, nonlinearities and parameter uncertainties make the system control a bit harder. Similarly, a study comparing the effectiveness of the two promising controllers is limited. Model Predictive Control (MPC) which have been known due to their ability in predicting the future behavior of a system (motor) and accommodating of constraints Also, Nonlinear PID (NPID) which was an upgraded version of conventional PID so as to handles the system nonlinearities and uncertainties. This study presents a comparative evaluation of Model Predictive Control (MPC) and Nonlinear PID (NPID) for regulating the speed of a BLDC motor. A comprehensive transfer function which captures both electrical and mechanical dynamics of the system was formulated from the mathematical model and the controllers were both developed and analyzed in MATLAB/Simulink. The performance metrics which includes rise time, settling time, and overshoot percentage are measured. The simulation outcomes highlights that the NPID demonstrates a quicker response, while the MPC reduces overshoot and a smoother transient performance. Additional input signals, such as sine waveform, square waveform, and ramp were applied to evaluate the tracking capability, revealing that NPID possess a slightly better tracking ability under all the conditions. This finding reveals the ability of both advanced control algorithms in addressing the nonlinearities and parameter uncertainties of the motor.

Keywords: Brushless DC motor (BLDC), Model Predictive Control (MPC), MATLAB/Simulink, Nonlinear PID (NPID), Speed Regulation.

1.0 INTRODUCTION

The proper regulation of an electric motor heavily depends on effective controllers to ensure accuracy, stability, and efficient operation, most especially when motors under varying loads, or environmental factors. However, the implementation of such effective controllers is difficult due to the electric motors nonlinearity and parameter uncertain, which simply means their meaning their output does not remain constant across all operating conditions. Furthermore, the motor's internal parameters such as resistance R, inductance I, and back-EMF constants usually varies due to factors like temperature, aging, or humidity, causing the system control more challenging. Brushless DC (BLDC) motors faces more of the difficulties listed above because of its nonlinear characteristics. Therefore, the motor needs an effective control technique that can handles the changes properly without causing instability or an overshoot. Due to this, BLDC motor speed control really requires an authentic and highly robust controllers capable of handling those factors. [1][2].

Several attempts were made by research contributors to counter the problem which includes Classical controllers such as Proportional-Integral-Derivative (PID) and Proportional-Integral (PI), are widely tested for BLDC motor speed regulation because of their implementation simplicity [3][4]. However, the controllers deteriorated when dealing with nonlinear system like BLDC motor. Intelligent controllers such as ANFIS [5], ANN [6] and Fuzzy logic [7] were all applied for BLDC motor speed control due their robustness and accuracy. However, rules formations, computational intensive, interpretation and tuning difficulties are their major problems.

Advanced controllers such as Model Predictive Control (MPC) and Nonlinear PID (NPID) are capable of handling multi input and multi output system (MIMOS) and nonlinear system such as BLDC motor to achieve a proper speed regulation [8][9]. A report on effectiveness and the capabilities of the two advanced controllers under same condition is limited.

This research presents a performance comparison of MPC and NPID controllers for BLDC motor speed control using MATLAB/Simulink. Furthermore, this study contributes to the body of knowledge by offering recommendations for selecting appropriate controllers based on system requirements.

1.1 Theoretical Background

The section discusses on the theories and the equation governing the study

1.1.1 Mathematical Modelling of BLDC Motor

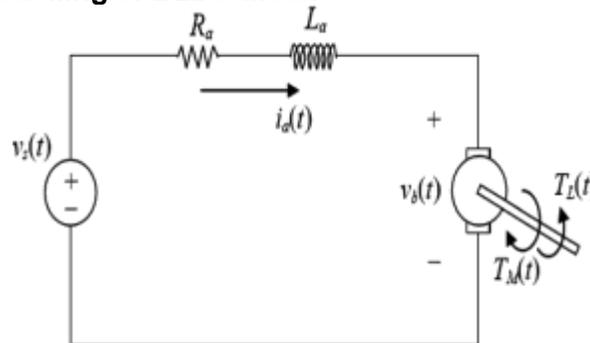


Figure 1. BLDC motor dynamics representation

The BLDC motor diagram described R_a = armature resistance, L_a = armature inductance, i_a = armature current, m = motor, j = rotor inertia, f = viscous friction, w = angular Velocity, θ = angular position.

From Faraday's law of electromagnetic induction, the back electromotive force (EMF) is proportional to the angular velocity ω_m (rad/s).

$$E_B = K_B \omega_m(t) \tag{1}$$

The motor Torque T_m is proportional to the armature current i_a by a Torque constant K_t from the Lorentz force.

$$T_m(t) = K_t i_a(t) \tag{2}$$

The mechanical operation of the BLDC motor

$$T_m = j \frac{d\omega_m}{dt} + f_m \omega_m + T_L \quad \text{But the Torque load } (T_L) \text{ is considered zero} \tag{3}$$

The voltage across the armature resistance, inductance, and back EMF is given as

$$E_a(t) = R_a i_a(t) + L_a \frac{di_a}{dt} + E_b(t) \tag{4}$$

In S-domain equation 5 becomes.

$$E_a(s) = R_a i_a(s) + sL_a i_a(s) + E_b(s) \tag{5}$$

The armature current derived from equation (5) to s-domain is given as

$$i_a(s) = \left(\frac{1}{L_a s + R_a} \right) (E_a(s) - E_b(s)) \tag{6}$$

The motor Torque T_m shown in equation (2) in time domain is now converted to S-domain given as

$$T_m(s) = K_t i_a(s) \tag{7}$$

The mechanical dynamics of the motor given in equation (3) is now converted to S-domain which is given as

$$T_m = J s w(s) + f w(s) + T_L \quad \text{Since, } T_L = 0 \tag{8}$$

To obtain the angular velocity (w) in S-domain is given as

$$T_m = (J s + f) w(s) \tag{9}$$

Angular velocity (w) in S-domain is given as

$$w(s) = \frac{1}{(J s + f)} T(s) \tag{10}$$

The back EMF E_b from equation (1) in Time domain is now derived in S-domain and is given as

$$E_b(s) = k_b w(s) \tag{11}$$

For the angular displacement (Θ) in S-domain is,

$$\frac{d\theta}{dt} = w \quad \text{This implies } s\theta(s) = w(s)$$

$$\Theta(s) = \frac{1}{s} w(s) \tag{12}$$

The ratio of output to the input which is the transfer function of the BLDC motor is given by

$$\frac{\Theta(s)}{E_a} = \frac{k_t}{s\{(R_a + L_a s)(sJ + f) + k_t k_b\}} \tag{13}$$

The equation (13) shows the Transfer function of BLDC motor which comprises both the electrical and mechanical elements such as resistance R_a , torque constant k_t , inductance L_a , Back EMF k_b , viscous friction f , rotor inertia J , source voltage E_a according to [10].

1.1.2 Nonlinear PID (NPID)

The NPID controller was design to improve the control performance beyond that of conventional PID controller. The NPID controller modifies the proportional, integral, and derivative gains in such a way that the gain varies with time to handles the nonlinear behavior of the motor under varying conditions.

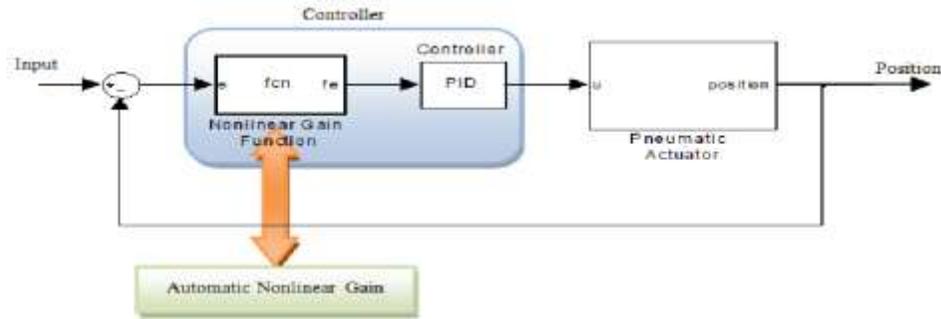


Figure. 2 Nonlinear PID block diagram [12].

The Matlab function block in the NPID block diagram shown in fig.2 contains the nonlinear gain function of the controller. These gain involves parameter such as the e_{max} which is the maximum limit of the error, K_o which is the overall controller strength, the hyperbolic tangent function (\tanh) and Alpha are meant to handles the aggressiveness of the system.

1.1.3 Model Predictive Control (MPC)

Model predictive control is a type of control algorithm that has been applied practically and through simulation means to handle different systems either complex or simple, linear or nonlinear and multi-input or multi-output (MIMO). The technique uses the process model to predict the future output response of a system. However, at each step, the control strategy tries to optimize plant behavior by adjusting the manipulated variable [13]. The controller's prediction capability combines with the classical feedback operation allows the algorithm to make adjustments for desired performance.

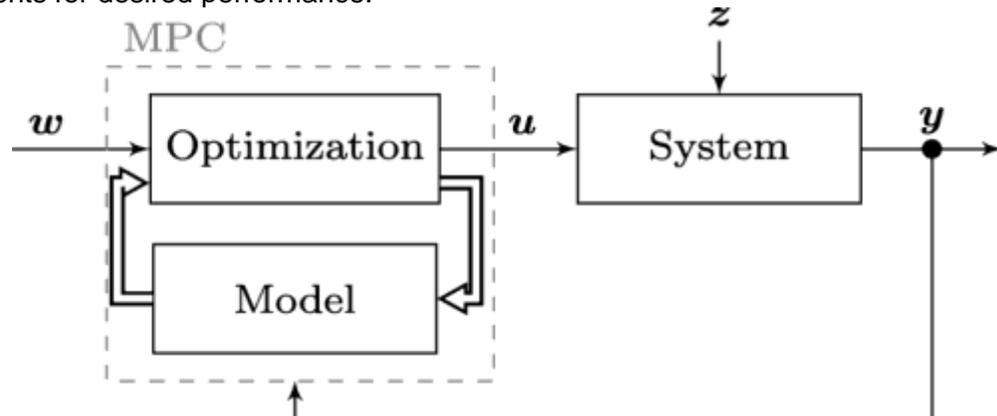


Figure 3. Simplified block diagram of a MPC-based control loop [8].

In designing an MPC controller, parameters such as control horizon (N), prediction horizon (P), model horizon (NM), sampling time (Ts), Weight factor and Constraints are very essential as this would lead to an effective and robust controller [14].

2. METHODOLOGY

The section discusses on the software environment, BLDC motor modeling, controller design, and simulation procedure.

2.1 Software Environment

This study considered the use MATLAB/Simulink as the key software environment for the design, and performance simulation of the controller. MATLAB/Simulink provides a high-capacity, model-based design framework that supports the development and analysis of complex dynamic systems with a high degree of numerical accuracy. Its computational robustness enables efficient handling of nonlinear models, iterative optimization routines,

and real-time response simulations required for advanced control strategies such as Model Predictive Control (MPC).

Among the features of the MATLAB/Simulink, it has library which contain some predefined blocks particularly those relating to electric drives, control algorithms, and system dynamics, allows for precise representation of the nonlinear behavior of BLDC motors. The software also enables parameter tuning tools, and a stable simulation environment, which reliable performance comparison between the MPC and NPID controllers. There MATLAB/Simulink software was considered due to its reliability and cost-free advantages, its suitability for both classical and advanced controller, and its ability to provide accurate result.

2.2 Simulation procedure

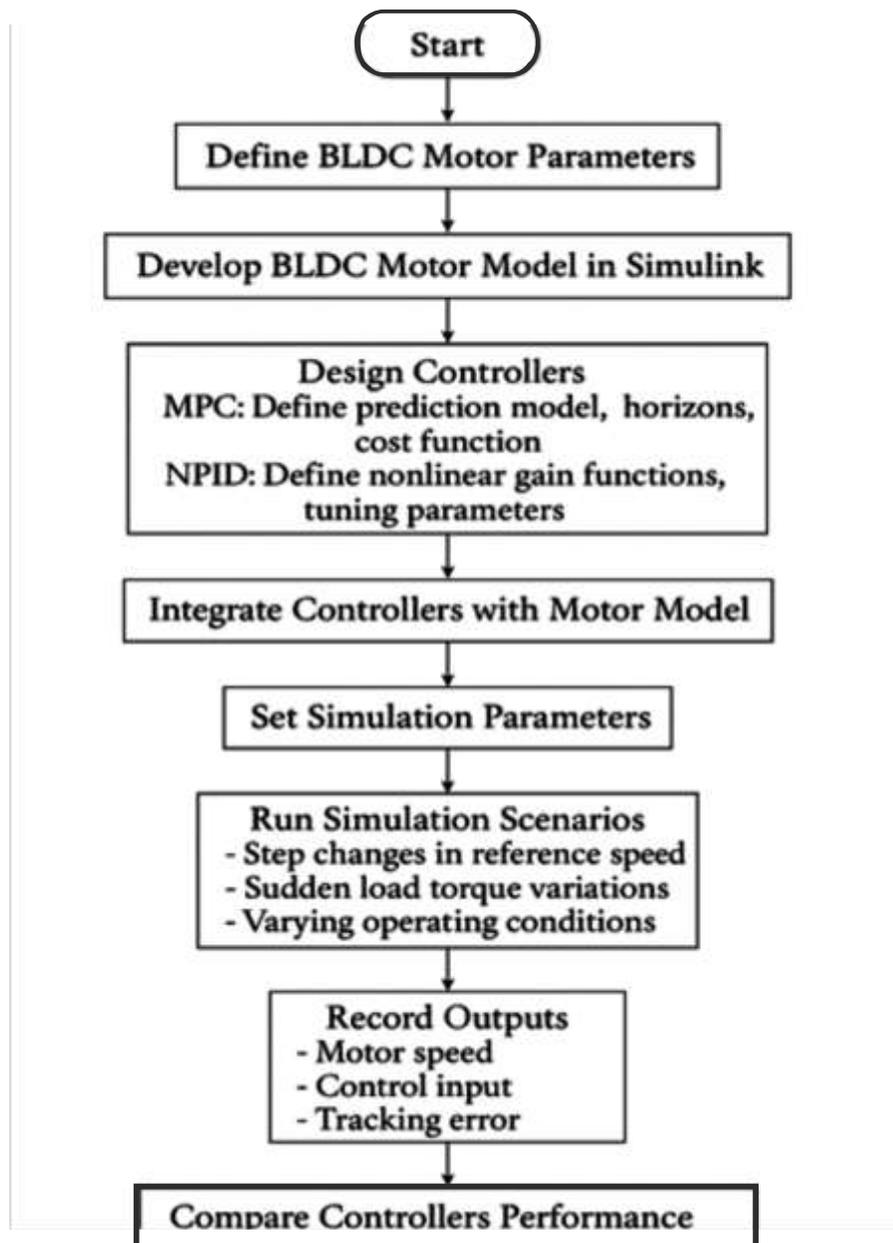


Figure 4. Simulation procedure for MPC and NPID controllers

Table 1. Simulation parameters

	Motor parameters	Values
1	Armature resistance R_a	1.0 Ω
2	Armature inductance L_a	0.046H
3	Torque constant k_t	14.48Nm/A
4	Viscous friction f	0.08Nms/rad
5	Back EMF k_b	0.55Vs/rad
6	Moment of inertia J	0.093J(kg/m ²)

However, the transfer function which was shown in equation (13) was simplified using the simulation parameters shown in Table 1. is now given as [11].

$$\frac{\Theta(s)}{E_a} = \frac{14.48}{2.44 \times 10^{-6} s^2 + 0.0161s + 1}$$

3.0 RESULTS AND DISCUSSION

The section presents the software simulation results of BLDC motor obtained from the research carried out using matlab/Simulink.

3.1 Software Simulation Results

A. Unit step response test

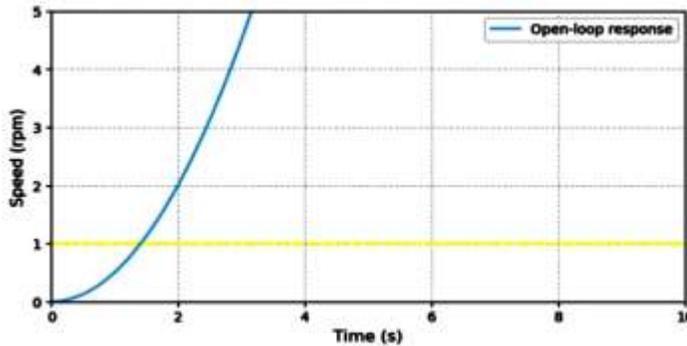


Figure 5. open loop response with step

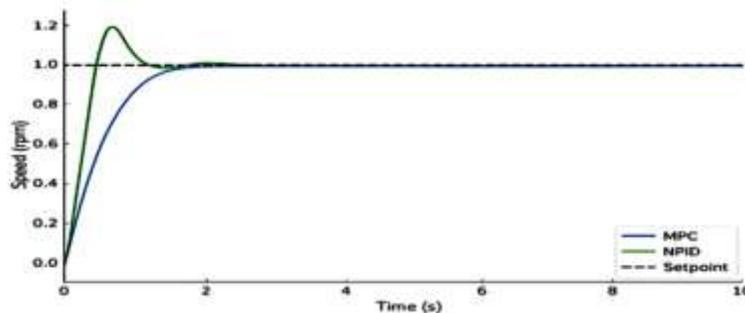


Figure 6. Performance of step response with NPID and MPC

The output waveform shown in Figure 5. highlights the performance of unit step response with NPID and MPC. The NPID controller demonstrates a faster rise time of 0.78sec but with a slight overshoot of 2.0% due to oscillation as observed in the waveform. While the MPC controller demonstrates a shorter settling time of 0.9800 and with minimal overshoot of 0.0616%. The results indicate systems requiring a precise control, sharp response, and

speed deviation reduction would consider the two controllers compared to classical controllers such as PID [3]. Step response values were given in table 2.

Table 2. Step Response

Controller	Step Response		
	Rise Time(s)	Settling Time(s)	Overshoot (%)
NPID	0.7893	1.0198	2.0930
MPC	0.8000	0.9800	0.0616
PID	0.2930	7.8600	35.232

B. Sine-waveform tracking test

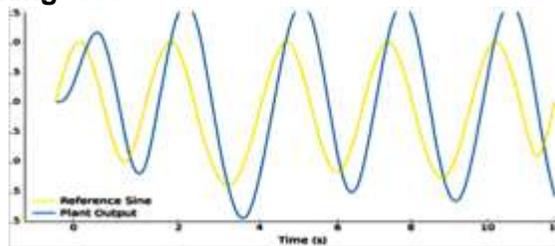


Figure 7. Open Loop Response

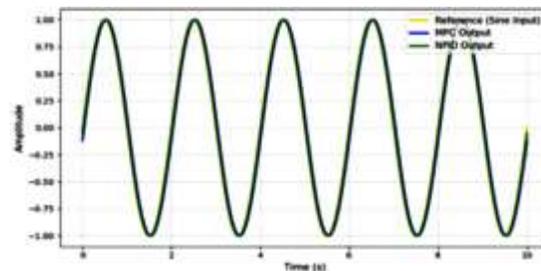


Figure 8. Closed Loop Response (MPC vs NPID)

This is a sine wave signal tracking test, whereby the set-point changes in sinusoidal form (from 0 to +1 to -1) as shown in Figure 7. The NPID controller demonstrate a good tracking accuracy with approximately 0% steady-state error. While the MPC controller shows a slightly phase mismatch with about 1.2% steady state error. However, the superior tracking accuracy of the NPID subjected to low current, mechanical torque stability, constant disturbance rejection.

C. Square waveform tracking test

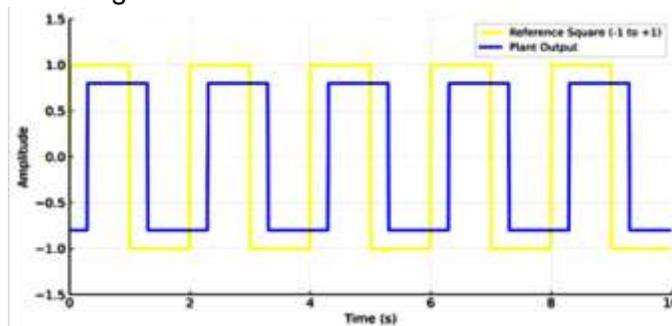


Figure 9. open loop response

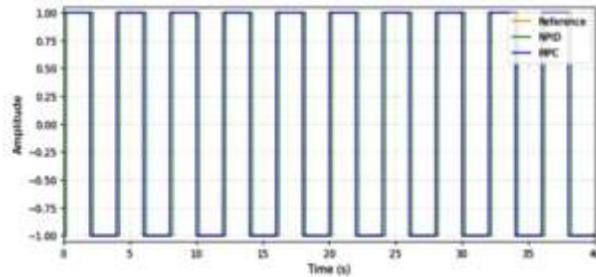


Figure 10. closed loop response (MPC vs NPID)

This is a square wave signal tracking test, whereby the set-point changes from +1 to -1 as shown in Figure 9. The NPID controller demonstrate a good tracking accuracy with minimal lag in term of shape and phase of the waveform (reference) which clearly shows the controller will be good for on/off system. While the MPC controller highlights a slightly poor tracking of the reference signal likewise phase/shape lagging compared to NPID. This signifies that both controllers can handle well an on/off systems (switch) properly compared to [15] [16].

D. Ramp waveform tracking test

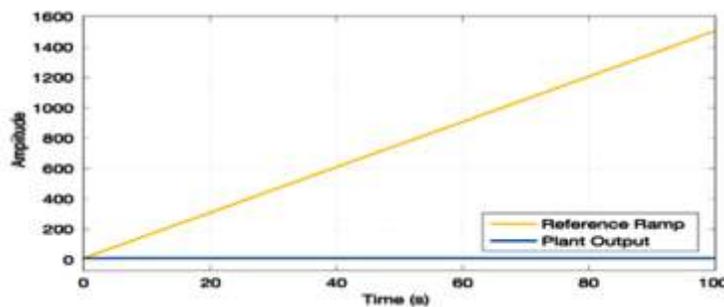


Figure 11. Open Loop Response

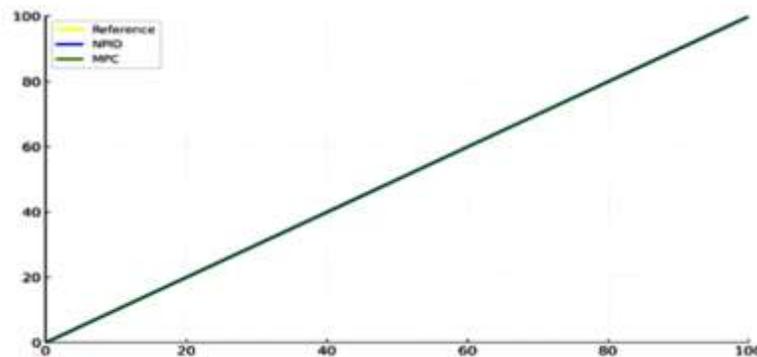


Figure 12. closed loop response (MPC vs NPID)

In the Ramp closed loop tracking test, the NPID controller demonstrate a perfect reference tracking ability with zero steady-state error as shown in Figure 11. while, the MPC comes with a slight error which approximately equal to 0.2%. However, both the two controllers demonstrate a good tracking test but the NPID is slightly ahead of MPC in-term of tracking performance and will fit the requirement of system (BLDC) especially during temperature rise, motor speed increase compared to [16].

4. CONCLUSION

The paper presented a performance comparison of model predictive control (MPC) and Nonlinear PID (NPID) for BLDC motor speed control. The simulation results obtained indicate that the NPID possess a faster response with approximate value of 0.78sec, while MPC minimizes overshoot with a value of 0.0616% which offered smooth transient response. Furthermore, others test input signal were also applied to test the tracking ability of the two controllers whereby the NPID slightly outperformed the MPC when tracking the sine-waveform, square waveform and the ramp signal. This finding demonstrates the effectiveness of the advanced control techniques in handling the BLDC motor nonlinearities and parameter uncertainties.

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