



Control of Switched Reluctance Motor Using Model Predictive Controller

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ABSTRACT

Switched Reluctance Motors (SRMs) have gained prominence in variable speed and electric propulsion applications due to their significant advantages. However, due to parameter variations and intricacies of phase commutation of the SRM, achieving optimal speed control on load torque variation has posed a great challenge to its speed control. The existing Proportional Integral Derivative (PID) controllers have been employed by researchers to regulate the speed and torque of various motors. Still, their effectiveness is hindered by the non-linear nature of SRMs and the associated parameter variations. Therefore, this study dealt with speed control of SRM using a Model Predictive Controller (MPC) to achieve dynamic control performance under diverse operating conditions. The mathematical model of the SRM was formulated based on its electromechanical torque characteristics. A Model Predictive Control (MPC) strategy was developed based on the formulated SRM model to achieve speed control. The model was simulated to control SRM using MATLAB 2020Ra Simulink environment. The performance evaluation of the suggested MPC model was done using rise time, percentage overshoot, and settling time as metrics, and the comparison was carried out with the conventional PID controller. The rise time, settling time, and percentage overshoot obtained for the model predictive controller were 4.38 seconds, 2.17 seconds, and 13.44%, respectively. The rise time, settling time, and percentage overshoot obtained for the PID controller were 1.16 seconds, 19.47 seconds, and 36.86%, respectively. The outcome of this study showed that the MPC controller performed better in terms of percentage overshoot and settling time as compared with that of the conventional PID controller. The Model Predictive Controller (MPC) can be useful in a chemical plant for temperature, pressure, flow, and composition control.

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INTRODUCTION

Electric motors are electrical machines used in electric propulsion systems to convert electrical energy into mechanical energy. They operate through the interaction between electromagnetic field windings and current to generate forces for propulsion. In addition, they can function in reverse as generators to recover energy during braking, such as in regenerative braking (Muthulashmi & Dhanasekaran, 2019). The major types of motors used in electric propulsion systems include Direct Current (DC)

Motors, Permanent Magnet (PM) Motors, Induction Motors (IM), and Switched Reluctance Motors (SRM) (Beno & Marimthu, 2020). The Switched Reluctance Motor (SRM) operates based on reluctance torque. Unlike brushed DC motors, power is delivered to windings in the stator rather than the rotor. This simplifies mechanical design by eliminating the commutator, but it complicates electrical design since a switching system must supply power to different windings while minimizing torque ripple.

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Some sources classify it as a type of stepper motor. SRMs are suitable for applications requiring high-speed operation, full torque, fault tolerance, simple control, high efficiency over a wide constant-power range, and robust torque-speed characteristics (Zeraouia & Benbouzid, 2019). These advantages make SRMs an economical alternative to DC, IM, and PM motors. However, their nonlinear electromagnetic properties and winding currents under saturation make analytical modeling difficult, especially for torque ripple reduction and steady-state speed control (Chan, 2020).

Over the past decades, SRMs and Switched Reluctance Drives (SRDs) have been extensively developed. In a reluctance machine, torque is produced by the rotor's tendency to move toward a position of maximum inductance in the excited winding (Karol-Wrobel, 2020). SRMs have salient poles on both rotor and stator and function similarly to variable-reluctance stepper motors, except that phase currents are switched on and off at precise rotor positions depending on speed and torque. This switching mechanism defines the SRM. Since the motor cannot function without its electronic controller, its performance relies heavily on drive design. Despite their nonlinear characteristics, SRMs are attractive due to their simple structure, low manufacturing cost, minimal maintenance, and the cost-effectiveness of unipolar power converters.

Traditionally, Proportional-Integral-Derivative (PID) controllers have been applied to brushless DC motors because of their simplicity. However, for nonlinear SRM drives, PID control often yields poor performance since a precise mathematical model is difficult to obtain (Tekam, 2018). This limitation has motivated the adoption of advanced techniques such as Model Predictive Control (MPC), which offers superior performance under varying operating conditions (Song, 2018).

Model Predictive Control (MPC) is an optimization-based framework, often referred to as moving horizon or receding horizon control. At each sampling instant, MPC computes the optimal control input by solving a finite-horizon optimization problem, using the current system state as the initial condition. Unlike traditional

controllers, MPC updates control actions in real time, accounting for model mismatches and constraints (El-Youssef et al., 2009). Thus, MPC enables parameter optimization and enhanced control of SRMs during online operation (Song, 2018).

Previous works demonstrate efforts to enhance motor control through advanced strategies. Preindl (2013) designed a cascade torque-speed MPC loop, achieving improved stability but with minor torque ripple. Ibrahim and Hassan (2015) optimized a PI-Fuzzy Logic controller using a Multi-Objective Genetic Algorithm for induction motors, reducing power consumption and overshoot. Haroutuon (2017) developed a nonlinear SRM model incorporating winding harmonics, validated through experiments. Ouanjli et al. (2019) reviewed Direct Torque Control enhancements, emphasizing ripple minimization. These studies underline the growing shift toward intelligent and predictive control methods. This paper develops and validates an MPC framework for SRM speed control using MATLAB/Simulink. The performance of MPC is evaluated and compared against a PID controller under varying operating conditions, focusing on dynamic response indices such as rise time, settling time, and overshoot.

Switched Reluctance Motor (SRM)

Switched reluctance motor (SRM), also called variable reluctance motor, is gaining interest in industrial applications such as electric vehicles and wind energy systems due to its simple and rugged construction. SRMs have better efficiency, better reliability, high fault tolerance, high constant power speed ratio (CPSR), and resistance to high temperatures compared with other types of motors, such as induction motors, permanent magnet synchronous motors, and brushless DC motors. The development in power electronics converters and their latest control techniques are the main reasons for the increase in the usage of SRMs.

SRM consists of a stator and rotor cores, which are made up of a stack of laminated electrical steel sheets. The coils are wound

directly on the stator tooth, or they can be wound on the bobbin and then inserted into the stator tooth to achieve a higher coil fill factor. The rotor with salient poles is free from the magnets and windings. (Sumeet 2022)

The term switched comes from the fact that the motor depends heavily on power switching transistors for its operation. The switched reluctance motor has salient poles on both the rotor and the stator and operates like a variable-reluctance stepper motor except that the phase current is switched on and off when the rotor is at precise positions, which may vary with speed and torque. It is this switching which gives the switched reluctance motor its name. This type of motor cannot work without its electronic drive or controller. This motor can be used for both low and high-power applications (Lee et al., 2009).

Basic principles and its characteristics

Switched reluctance motor has emerged as an alternative to DC and AC motors only in the past few decades because of the availability of high power and high-speed semiconductor switches and availability of microcontrollers for complex control problems. The SRM is topologically and electromagnetically identical to the variable reluctance (VR) stepper motor although there are differences in engineering design and control methods. Since the principle of operation of SRM is based on the variation of inductance (or reluctance), it is also often called as variable reluctance motor (VRM). At low power levels, the SRM can be considered as an alternative to costly brushless DC motor (BLDC motor). At high power levels, the SR motor is a viable substitute to induction motor and DC motors (Zwyssig et al., 2017).

Switched Reluctance Motors (SRMs) possess distinctive characteristics that set them apart from other types of motors. Firstly, both the stator and rotor in SRMs feature salient poles, contributing to their unique design and operational principles. Unlike some conventional motors, the number of rotor poles in an SRM does not match the number of stator poles,

introducing asymmetry in the system. Notably, SRMs lack magnets or windings on the rotor, differentiating them from permanent magnet or induction motors. Furthermore, the magnetic flux and current in SRMs do not follow a sinusoidal pattern, adding complexity to their control and modeling. Another defining feature is the very low mutual inductance among phase windings, influencing the motor's behavior during dynamic operations. Lastly, the generated torque in SRMs is independent of the sign or polarity of the stator current, leading to the prevalent use of unipolar power converters in their control systems. These distinct properties collectively contribute to the unique characteristics and challenges associated with the control and optimization of switched reluctance motors.

All the above features make traditional vector diagrams and equivalent schemes for other motors not very much suitable for SRM analysis.

Features and industrial applications of SRM

Simple construction is a prime feature of the SRM. The SR motors eliminate rotor windings, permanent magnets (PMs), brushes, and commutators. With no rotor windings, the rotor is basically a piece of steel (and laminations) shaped to form salient poles. The absence of brushes provides long life. The absence of permanent magnets and rotor winding reduces the cost. Besides, SR motors have some other attractive advantages that make them favourable for various industrial applications. In summary, the main advantages of the SRM include (Gerada et al., 2019).

SRM Drive System

A typical SRM drive system comprises a DC power supply, a power converter, current/voltage sensors, the controller, SRM, a position sensor, and the load. The diagram of the main components is shown in Figure 2.1. The controller receives the external command signal, such as reference speed or torque and calculates the switching control signals for the switching devices in the power converter so that appropriate current is regulated in the stator circuits. The switching control signals are

calculated based on a control strategy, the feedback signals (current, voltage, and rotor position), and the power converter topology (Fairall et al., 2015).

Methods of Controlling SRM

The operation of SRM is based on reluctance torque instead of continuous torque, such as that in synchronous motors. This nature leads to high torque ripple and a highly nonlinear magnetization characteristic. The generation of torque depends on the switching action according to rotor position, which is why one of the common controls of SRM is switching angle control, where the engineer may choose appropriate turn-on and off angles. Current controls such as soft/hard chopping and hysteresis is also frequently used. Generally, current control is applied in a low-speed region where the current has enough time to rise to its maximum value, so it is controlled to adjust to the desired performance (Kunz et al., 2018). On the other hand, angle control is used for high-speed operation where the time is not enough for the current to rise; that is, while the on/off angle is controlled to allow more current flow. Control methods can be categorized based on scalar or vector control, as shown in Figure 2.2.

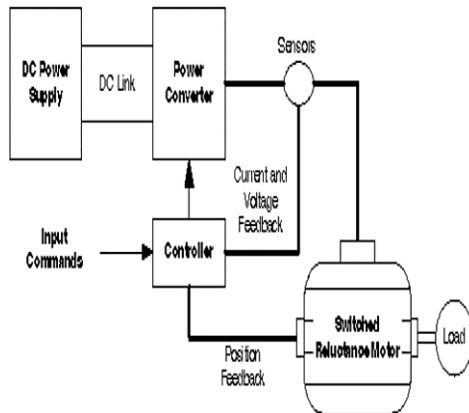


Figure 1: Diagram of SRM Drive System (Fairall et al., 2015).

Switched Reluctance Motor Mathematical model

The block diagram shown in Figure 1 is used to establish the mathematical equations of switched reluctance motor for control application. The armature is modeled as a circuit with resistance connected in series with an inductance and a voltage source representing the back electromotive force in the armature when the motor rotates.

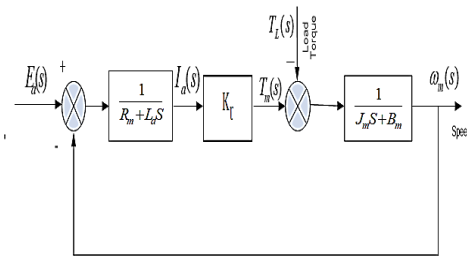


Figure 2: Block Diagram for the SRM Mathematical Equation

For linear analysis of SRM, the torque developed by the motor is proportional to the air gap flux and armature current. Thus, the electromechanical torque of SRM equation is given as (Umar et al., 2024):

$$\tau_m(t) = K_m(t)\phi I_a(t) \quad (1)$$

The voltage generated in the armature coil of the motor is the back EMF, given as:

$$e_b(t) = K_b \omega_m(t) = K_b \frac{d\theta}{dt} \quad (2)$$

Equation for the armature circuit

$$e_a = R_m i_a + L_a \frac{di_a}{dt} + e_b \quad (3)$$

Taking the Laplace transform of equation (2) and (3)

$$E_b(s) = K_b S \Theta_L(s) \quad (4)$$

$$E_a(s) = R_m I_a(s) + L_a S I_a(s) + E_b(s) \quad (5)$$

Substituting equation (3.4) into (3.5) yield,

$$E_a(s) = R_m I_a(s) + L_a S I_a(s) + K_b S \Theta(s) \quad (6)$$

Therefore, from equation 3.6

$$I_a(s) = \frac{E_a(s) - K_b S \Theta_L(s)}{(R_m + L_a S)} \quad (7)$$

The application of Laplace transforms to equation (7) yields

$$T_m(s) = K_\tau I_a(s) \quad (8)$$

Where:

$$K_\tau = K_m(t)\phi \quad (9)$$

Since,

$$T_m(s) = T_L(s) + T_d(s) \quad (10)$$

3.10

$$K_\tau \left(\frac{E_a(s) - K_b S \Theta_L(s)}{R_m + L_a S} \right) = J_L S^2 \Theta_L(s) + B_M S \Theta_L(s) \quad (14)$$

$$G_c(s) = \frac{\Theta_L(s)}{E_a(s)} = \frac{K_\tau}{J_L L_a S^3 + (J_L R_m + B_m L_a) S^2 + (B_m R_m + K_\tau K_b) S}$$

Development of the Mathematical Model for Switched Reluctance Motor Speed Control Using MPC

The popular models used in MPC algorithms are impulse and step response. To quantify the predicted outputs, various types of discrete models are used. Applying the step response to the system, the modelling parameters can be determined by evaluating the system

Where:

$T_L(s)$ = Load torque

$T_d(s)$ = Disturbance torque

Assuming that the disturbance torque is negligible, the load torque is equal to the motor torque.

$$T_L(s) = T_m(s) \quad (11)$$

$$T_L(s) = J_L S^2 \Theta_L(s) + B_M S \Theta_L(s) \quad (12)$$

3.12

$$T_m(s) = K_\tau \left(\frac{E_a(s) - K_b S \Theta_L(s)}{R_m + L_a S} \right) \quad (13)$$

Therefore, from equation 13

output. The basic concept of the MPC is that it calculates future controls based on current measurements via the solution of predictive control strategy, but only the first element of controls is applied to the process in Figure 3.2. The objective function of the predictive control strategy has been formed in Equation (15) and subject to the mathematical model in Equation (3.1) to (3.15).

$$u_n(k+1), \dots, u_n((k+M)) \sum_{n=1}^4 \sum_{l=1}^p [w_1 (y_p(k+l) - y_{sp}(k+l))^2 + w_2 (\Delta u_n(k+l-1))^2] \quad (15)$$

where:

$$u_{n, \min} < u_n(k+l) < u_{n, \max} \quad \text{for } l = 1, 2, \dots, M$$

$$y_{p, \min} < Y(k+l) < Y_{p, \max} \quad \text{for } l = 1, 2, \dots, p$$

$$Y(k+p) = Y_{sp}$$

The objective function of the MPC is to minimize the sum of squares of the errors between the predicted outputs and the set point values and also to optimize the control movements evaluated over the prediction horizon. The realization of SRM speed control is presented in Figure 3.2. The supply voltage that is applied to the circuit is

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The simulation of speed control of the SRM is performed using MATLAB/SIMULINK software. This led to a control system in which the speed was controlled by adjusting the reference current. Figure 3.3 and Figure 3.4 shows the Block diagram for the Model Predictive Control and the Simulink model of the SRM system with MPC and PID controllers respectively.

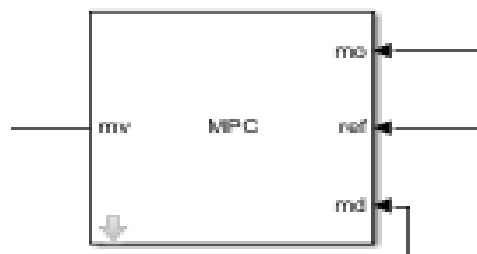


Figure 3: Model for SRM Speed Control Using Model Predictive Controller



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Performance Evaluation

The performance characteristics for the MPC speed control of SRM model were evaluated based on rise time, settling time, percentage overshoot and compared with the existing PID model. The rise time is the time taken for the transient response to move from 10% to 90% of the steady state responses. This performance metric reflects how fast the motor can respond to torque demand changes, or how fast it takes to reach the target speed. The settling time is the time after which the output is within a specified band around the steady state value. This parameter is indicative of how fast and smoothly it takes for the motor output to reach steady state after a change in disturbance or command occurs. The specified band of disturbance is usually within 1% to 5% of the steady state value. Lastly, the maximum overshoot is the maximum peak value of the responses curve measured from the desired response of the system. This metric is used to evaluate how effectively the MPC suppresses transient deviations in speed, torque, and current compared to conventional controllers.

Simulation of Switched Reluctance Motor Without Controller

Based on the Switched Reluctance Motor (SRM) parameters in Table 4.1, a 240V DC power supply is utilized in the system. The converter maintains constant turn-on and turn-off angles at 45° and 75°, respectively, across various speed ranges. The reference current is set at 200A, with a selected hysteresis band of ± 10 A. Initiating the SRM involves applying a step reference to the regulator input. The acceleration rate is contingent on the load characteristics. Opting for a very light load of 5Nm is aimed at minimizing the startup time. Since only the currents are under control, the motor speed will progressively increase in accordance with the mechanical dynamics of the system. The resulting SRM drive waveforms, including magnetic flux in Figure 4.1 (a), phase voltages in Figure 4.1 (b), windings current in Figure 4.1 (c), motor torque in Figure 4.1 (d), and speed at No-load and Load of 5Nm in Figure 4.2 and Figure

4.3, respectively, are depicted on the scope as illustrated.

It is evident that the Switched Reluctance Motor (SRM) exhibits a substantial torque ripple component, attributed to the transitions of currents between successive phases. This torque ripple is an inherent characteristic of the SRM and is primarily influenced by the turn-on and turn-off angles of the converter. Upon observing the waveforms of the drive, it becomes apparent that the SRM's operational speed range in Figure 4.2 and Figure 4.3 can be categorized into two distinct regions based on the converter's operating mode: current-controlled and voltage-fed.

Table 4.1: SRM parameters used in the Simulink Model.

Motor parameter	Value
Rated Power	60kW
Number of Phases	3
Number of Stator Poles	6
Number of Rotor Poles	4
Aligned Phase Inductance	23.6mH
Unaligned Phase Inductance	0.67mH
Inertia	0.05Kg.m
Stator Resistance	0.05 Ω
DC Voltage Supply	240V
Reference Speed	1500rpm and 2000rpm
Load	5Nm

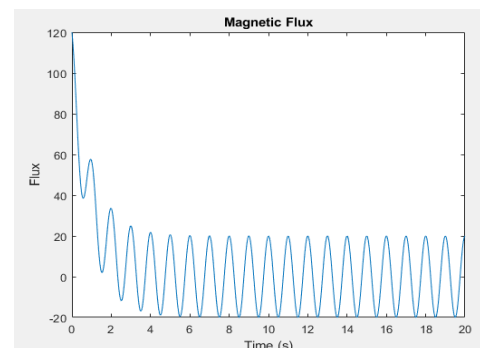


Figure 6: (a): SRM Magnetic Flux

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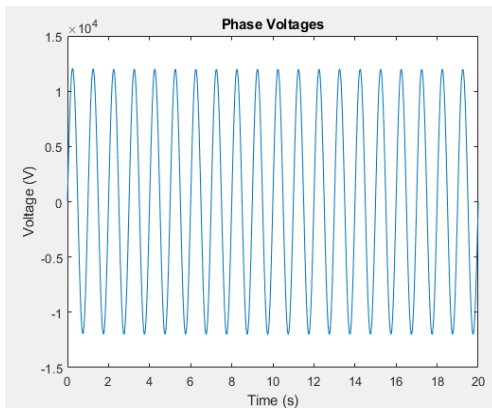


Figure 7 (b): SRM Phase Voltage

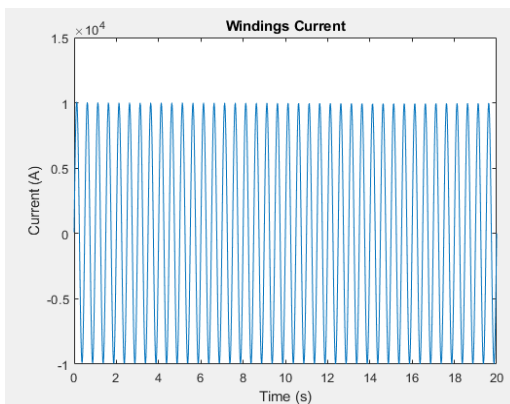


Figure 8 (c): SRM Windings Current

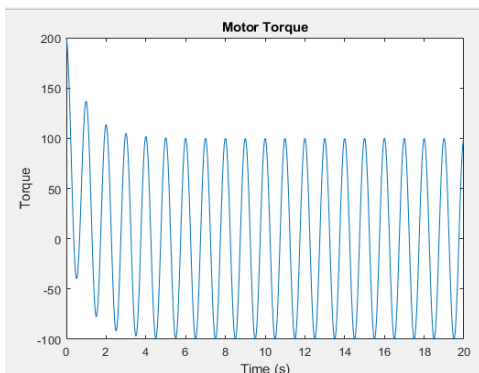


Figure 9: (d): SRM Torque

The Figure 4.2 below shows the speed response of a Switched Reluctance Motor (SRM) system operating without the aid of a Model Predictive Controller (MPC). These metrics are

fundamental in assessing the dynamic characteristics and efficiency of a control system. Firstly, the duration it takes for the speed response to reach its maximum overshoot called the Peak Time (T_p) is 0.93 seconds. This relatively short peak time suggests a swift achievement of the system's peak speed.

The Rise Time (T_r), measuring 0.4056 seconds, signifies the duration required for the response to ascend from 10% to 90% of its final value. This parameter implies a rapid rise in the speed response, reaching most of its eventual value in a short time span. The Settling Time (T_s), with a value of 14.01 seconds, represents the time needed for the system to stabilize within a certain percentage of its final speed. A prolonged settling time indicates that the system takes a considerable duration to attain a stable state around the desired speed.

The Overshoot, at 64.01%, reveals the percentage by which the speed response exceeds its steady-state value. This substantial overshoot implies a deviation from the desired reference speed (1500 rpm), potentially leading to instability or oscillations in the system. The overshoot speed of 2460 rpm specifies the actual speed at which the overshoot occurs. Figure 4.3 shows the speed response characteristics of a Switched Reluctance Motor (SRM) system operating without the incorporation of a Model Predictive Controller (MPC). These evaluations are conducted under a no-load condition, with the reference speed set at 1500 rpm. The peak time of 0.93 seconds signifies the duration taken for the speed response to reach its maximum value. This is also relatively short peak time that suggests that the system achieves its peak speed swiftly, indicating a responsive dynamic behavior.

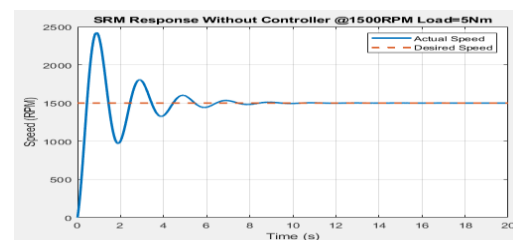


Figure 10: SRM Without Controller @1500rpm, Load=5Nm

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The concise rise time (T_r) measured at 0.41 seconds implies a rapid increase in speed, with the system attaining a substantial portion of its final speed in a short time frame. Settling time (T_s) of 11.98 seconds, reflects the duration required for the system to stabilize within a certain percentage of 2% of its final speed. Although not excessively long, this settling time indicates a moderate time frame for the system to achieve a stable state under no-load conditions. The Overshoot, measured at 62.62%, reveals the percentage by which the speed response surpasses its steady-state value. This considerable overshoot suggests that, in the absence of a load, the system significantly exceeds the desired reference speed of 1500 rpm before settling down.

The SRM system with and without an MPC controller demonstrates a speed response on load and under no-load conditions characterized by a swift peak time and rise time. The moderate settling time indicates a reasonable duration for the system to stabilize. However, the notable overshoot highlights a substantial deviation from the desired reference speed, prompting considerations for further analysis and potential adjustments to control strategies, such as the implementation of MPC to optimize performance and minimize overshooting under load and no-load conditions.

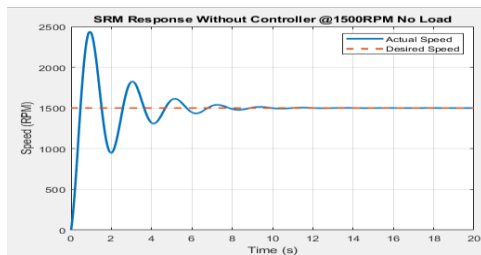


Figure 11: SRM Without Controller @1500rpm, No-load

Speed Control of SRM Using Model Predictive Control (MPC) Controller

The value of the constants of the MPC controller in the MATLAB Simulink are control cost M and prediction horizon N dependent on the system to be controlled, so after tuning

appropriately and testing for best condition, the values of the constant used for this analysis were, $M = 5$, $N = 10$. The reference speed was set at 1500rpm and 2000rpm and resulting response is displayed in the scope. The graph displayed on the scope is speed against time.

Speed Control of SRM using Model Predictive Control (MPC) at 1500 rpm

The speed response of the Switched Reluctance Motor (SRM) under a 1500 rpm reference speed was evaluated with the integration of a Model Predictive Controller (MPC), both at no-load and under a 5 Nm load condition. The performance of the MPC-controlled system is compared with that of the non-MPC case.

No-Load Condition (Figure 4.4):

At no load, the MPC controller introduces noticeable changes in the dynamic response. The rise time increases to 1.89 s compared to 0.41 s without MPC, while the peak time extends to 3.78 s from 0.93 s. These increases indicate that MPC emphasizes stability and controlled progression over rapid acceleration. Despite this, the settling time remains almost the same, with 11.91 s for the MPC case versus 11.98 s without MPC, showing minimal impact on stabilization duration. The most significant improvement is in the overshoot, which is reduced from 62.62% (2460 rpm) to 17.43% (1761 rpm). This substantial decrease highlights MPC's effectiveness in suppressing excessive speed deviations and enhancing system stability.

Loaded Condition (5 Nm, Figure 4.5):

When subjected to a 5 Nm load, similar performance trends are observed. The peak time with MPC increases to 3.96 s, compared to 0.89 s without MPC, reflecting a more gradual approach to maximum speed under load. Interestingly, the rise time remains unchanged at 1.89 s for both cases. The settling time improves with MPC, reducing to 12.95 s from 14.01 s, showing enhanced stabilization efficiency under load. Most importantly, overshoot decreases significantly from 64.01% (2460 rpm) to 16.71% (1751 rpm), confirming the robustness of MPC in limiting overshoot even in loaded conditions.

Across both no-load and loaded conditions, MPC introduces longer rise and peak times, favouring controlled dynamics over rapid response. However, it significantly reduces overshoot and slightly improves settling time under load, demonstrating its superiority in ensuring stable and efficient speed control of SRMs at 1500 rpm.

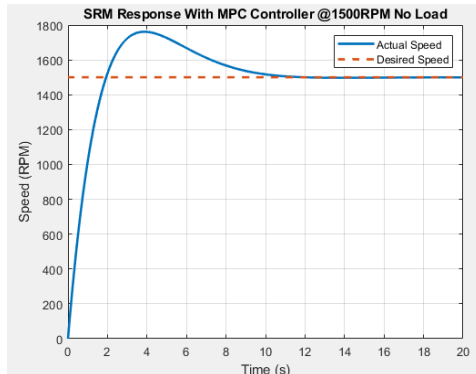


Figure12: SRM Speed Response With MPC, 1500rpm, No-load

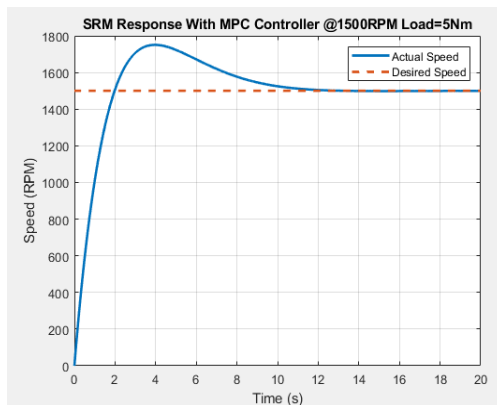


Figure 13: SRM Response with MPC Controller, 1500rpm, Load=5Nm

Speed Control of SRM using Model Predictive Control (MPC) at 2000 rpm

The performance of the Switched Reluctance Motor (SRM) system was further evaluated by increasing the reference speed from 1500 rpm to 2000 rpm under both no-load and a 5 Nm load condition, with the integration of a Model

Predictive Controller (MPC). The speed response characteristics are shown in Figure 4.6.

Under a 5 Nm load, the peak time increases slightly from 3.96 s (at 1500 rpm) to 4.38 s at 2000 rpm, while the rise time also shows a modest increase from 1.89 s to 2.17 s. This indicates that the system takes a little longer to reach 90% of the target speed, reflecting a balance between higher speed tracking and stability at the elevated reference speed.

The settling time experiences a more pronounced increase, rising from 12.95 s to 17.79 s. This suggests that the system encounters greater difficulty in stabilizing at the higher reference speed, likely due to the additional dynamic complexity introduced by the increased operating demand. Interestingly, the overshoot improves despite the higher speed target. It decreases from 16.71% (1751 rpm at 1500 rpm reference) to 13.44% (2269 rpm at 2000 rpm reference). This reduction demonstrates the robustness of the MPC controller in limiting overshoot and maintaining control, even when the system is subjected to a faster reference. The slight increase in overshoot speed value is consistent with the higher target speed but remains well-controlled. Increasing the reference speed from 1500 rpm to 2000 rpm results in longer rise, peak, and settling times, reflecting the system's greater challenge in stabilizing at higher speeds. However, the MPC controller continues to effectively suppress overshoot, confirming its capability to ensure stable and reliable performance across varying speed demands.

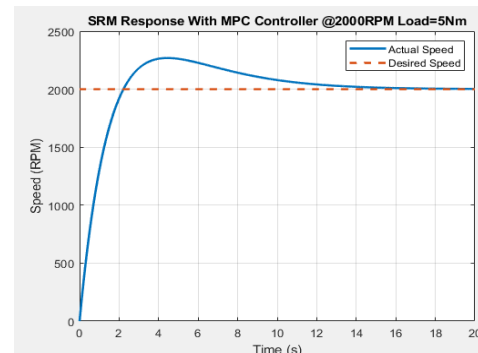


Figure 14: SRM Response with MPC Controller, 2000rpm, Load=5Nm

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Speed Control of SRM using Model Predictive Control (MPC) at 2000 rpm

The transition in the Switched Reluctance Motor (SRM) system from a reference speed of 1500 rpm to 2000 rpm under no-load conditions, guided by a Model Predictive Controller (MPC), exhibits discernible changes in the speed response as shown in Figure 4.7. The peak time increases only slightly, from 3.78 s at 1500 rpm to 3.79 s at 2000 rpm, indicating negligible variation. Similarly, the rise time records a minor increase from 1.89 s to 1.92 s, reflecting a relatively fast ascent toward the reference speed with minimal impact from the elevated speed setting.

The settling time shows a modest increase to 14.01 s, suggesting that the system requires a longer duration to stabilize around the 2000 rpm reference compared to the 1500 rpm case under no-load conditions.

A significant improvement is observed in the overshoot, which decreases from 17.43% (1761 rpm at 1500 rpm reference) to 13.56% (2238 rpm at 2000 rpm reference). This reduction highlights the MPC controller's effectiveness in mitigating excessive deviation, ensuring a controlled and stable response despite the higher reference speed.

Overall, the transition from 1500 rpm to 2000 rpm with MPC results in slight increases in peak time, rise time, and settling time, while overshoot is notably reduced. This demonstrates the adaptability and robustness of the MPC controller in maintaining effective speed regulation even under increased speed demands. In comparison, the performance of the SRM system using a PID controller at a 5 Nm load provides a contrasting behaviour. As shown in Figure 4.8(a), at a 1500 rpm reference speed, the system with PID control records a rise time of 1.20 s, a settling time of 16.59 s, and a percentage overshoot of 44.06%. Figure 4.8(b) further illustrates the response under different conditions, reinforcing the differences in dynamic performance between PID and MPC control strategies.

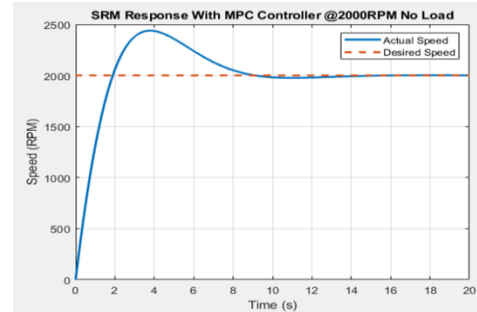


Figure 15: SRM Response with MPC Controller, 2000rpm, No-load

With the same load while the speed is increased from the initial 1500rpm to 2000rpm shows the rise time of 1.16 seconds, settling time of 19.47 seconds and percentage overshoot of 36.86%. The performance of the system with PID shows that the system performs better when the reference speed is increased to 2000rpm in terms of low rising time and lower percentage of the overshoot.

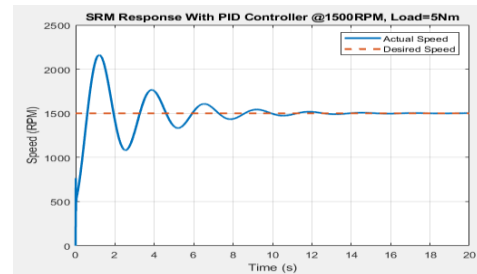


Figure 16 (a): SRM Response with PID Controller, 1500rpm, Load=5Nm

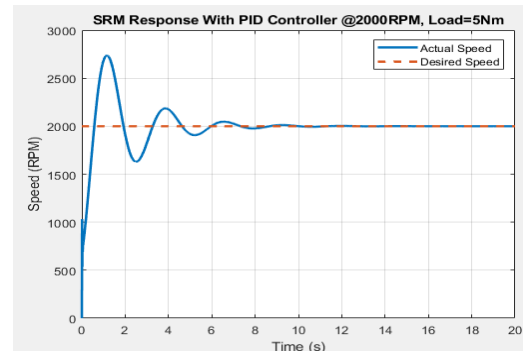


Figure 17 (b): SRM Response with PID Controller, 2000rpm, Load=5Nm

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RESULTS ANALYSIS WITHOUT CONTROLLER

SRM Without Controller

The result from the graph in Figure 4.5 (a, b) is compiled in Table 2 below, showcasing the performance of the SRM without MPC controller for load (5Nm) and no-load conditions. The presence of load indicates an increase more time for the system to settle, higher overshoot speed compares to the no-load situation.

SRM With MPC Controller At No-Load Condition

At No-load condition for both 1500 rpm and 2000 rpm, the results in Table 3 shows that when the speed were increased, all the metrics had slight increment, indicating that when speed is increased, there is a tendency for the system to take more time to rise, settled, and overshoot more.

At Load = 5Nm Condition

At this condition, the system perform all round better when the speed is at 1500 rpm (reference) than when it was increased to 2000 rpm just like at no-load condition (see Table 4). These results indicated that when the reference speed is at 1500rpm or lower, the SRM system tends to perform better using an MPC as the controller.

Comparative Analysis: Model Predictive Control (MPC) Versus Proportional Integral Derivative (PID)

A direct comparison between the MPC and a tuned PID controller was conducted. The results, summarised in Table 3 and visualised in Figure 8, reveal a clear trade-off. The PID controller achieved a faster rise time (1.20 s vs. 3.96 s at 1500 rpm). However, the MPC controller was vastly superior in terms of overshoot suppression (16.71% vs. 44.06%) and settling time (1.89 s vs. 16.59 s). This demonstrates that the MPC provides a much more stable and damped response

Table 1: Comparative Performance of SRM System with and Without MPC Controller

Ref. Speed (rpm)	Condition	Controller Type	Peak Time (s)	Rise Time (s)	Settling Time (s)	% Overshoot	Overshoot (rpm)	Actual Overshoot (rpm)
1500	No-load	Without Control	0.93	0.41	11.98	62.62	2430	930
1500	No-load	With MPC	3.78	1.89	11.91	17.43	1761	261
1500	Load = 5 Nm	Without Control	0.93	0.41	14.01	64.01	2460	960
1500	Load = 5 Nm	With MPC	3.96	1.89	12.95	16.71	1751	251
2000	No-load	With MPC	3.79	1.92	14.01	13.56	2438	438
2000	Load = 5 Nm	With MPC	4.38	2.17	17.79	13.44	2269	269

Table 2: Comparison of Results of MPC-Based SRM vs. PID-Based SRM

Ref. Speed (rpm)	Condition	Controller	Rise Time (s)	Settling Time (s)	Overshoot (%)
1500	Load = 5 Nm	MPC	3.96	12.95	16.71
1500	Load = 5 Nm	PID	1.20	16.59	44.06
2000	No-load	MPC	4.38	17.79	13.44
2000	No-load	PID	1.16	19.47	36.86

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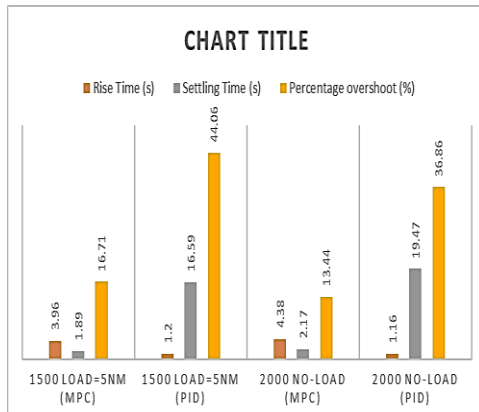


Figure 4.9: Chart Showing Performance of the MPC and PID Controllers

CONCLUSION

In this research, a more efficient speed control of switched reluctance motor (SRM) was achieved through the formulation of a mathematical model of a switched reluctance motor based on the electromechanical torque of the motor. The formulated (SRM) model was then used to develop a model predictive control (MPC) strategy for better speed control. The two models were later simulated and the results obtained were compared with respect to three key performance metrics which included the rise time, settling time and percentage overshoot. In a typical loading scenario of 5Nm and a load speed of 1500rpm the MPC model showed an increase in the rise from 1.20s to 3.96s. Reason being that the MPC control is focused more on the stability of the system. The settling time on the other hand decreased from 16.59s to 1.89s indicating its effectiveness in the stabilization of the system thereby reducing the time it takes to reach a steady state. The percentage overshoot decreased from 44.06% to 16.71%. This signifies a substantial enhancement in control as this model allows for the mitigation of excessive deviation from the reference speed thereby contributing to improved stability

RECOMMENDATIONS

Given the observed trade-offs, the choice between MPC and PID controllers should be based on the enhanced stability of the SRM system. For applications prioritizing reduced

overshoot and enhanced stability, MPC is recommended. The MPC controller can be useful in chemical plants for temperature, pressure, flow a compositions control. For scenarios where rapid response is crucial, PID may be considered. Both controllers can benefit from further tuning and optimization to strike an optimal balance between speed achievement and system stability. Fine-tuning these controller parameters more could lead to improved performance tailored to the SRM's characteristics and operational conditions.

RESEARCH GAP

While the existing studies have explored various control strategies for motors, including PID controllers, fuzzy logic, genetic algorithms, and direct torque control (DTC). However, it is observed that there is room for more improvement in the stability of the existing systems. This gap presents a compelling rationale for the adoption of MPC in the control system of SRMs. Therefore, the adoption of MPC for SRM speed control is not only justified based on its proven capabilities in other motor control applications but is also driven by the identified research gap in the existing literature like higher percentage overshoot and longer settling time. This choice aligns with the need for a tailored an advanced control strategy to optimize the performance of switched reluctance motors, considering their unique characteristics and operational challenges.

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