Republic of Iraq
Ministry of Higher Education
and Scientific Research
University of Misan
College of Engineering
Department of Electrical Engineering

Switched Reluctance Motor (SRM) Speed Control using a Hysteresis Current Controller

A graduation project submitted to the **Department of Electrical Engineering**, in partial fulfillment for the requirements for the award of the degree of Bachelor of **Electrical Engineering**

By

1- يعقوب حسين علي مسلم
2- محمد سالم جوحي
3- بتول حيدر طارق عنيد
4- علي ثامر طعمه

SUPERVISED BY

م. زهراء داوود

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بسم الله الرحمن الرحيم

((وَلَقَدْ آتَيْنَا دَاوُودَ وَسُلَيْمَانَ عِلْمًا ۖ وَقَالَا الْحَمْدُ لِلَّهِ الَّذِي فَضَّلَنَا عَلَىٰ كَثِيرٍ مِّنْ عِبَادِهِ

الْمُؤْمِنِينَ)) النمل اية(١٥)

صدق الله العلي العظيم

Content

List of figures

CHAPTER ONE

INTRODUCTION

Chapter One: Introduction

1.1 Introduction

In recent years, switched reluctance motors (SRMs) have been employed in adjustable-speed applications owing to theirnumerous advantages such as low costs, robust structure, absence ofpermanent magnet, high torque-to-current ratio, and high reliability.A simple controller cannot guarantee the quality of speed response in awide speed range because of the nonlinear inductance of SRM [1] . In the context of control of such motors, many studies on current and torquecontrol have been conducted in which torque ripple minimization is crucial [2,3] . Inherent torque ripple causes speed ripple in SRMs and thus generates vibra- tion and mechanical stress [4] . In addition to the currentand torque control of the SRM drive, speed-control performance attracts special interest in industrial applications. In general, SRMspeed can be conventionally controlled using a simple proportional–integral (PI) controller. However, the inherent nonlinearity and uncertainty of the SRM parameters compel researchers to proposemore advanced control techniques.

1.2 How is SRM controlled

Since, the introduction ofrenewable energy resources to the distributed power generationsystems, grid connected inverters and its control plays major role to the total energy production. However, due to stochastic behaviour of grid connected renewable resources, current control of inverter is most challenging. There are various techniques proposed in the literature for current control with both linear and nonlinear controller. Linear controller based on PWM modulation have better steady state response but having slow dynamic performance depends on type of connected load . Non-linear controllers have fast dynamic response, robustness toward parametric perturbations, but varying switching frequency and complex hardware implementation are major drawbacks. Among the various techniques, hysteresis current controller (HCC) offer fast dynamic response, easy to implement and robustness to output load parameter variation. One effective way to control speed is with a hysteresis current controller, which is a circuit that attempts to maintain the current within a specific range around your desired value. It's like setting limits on the current and preventing it from exceeding that limit.The idea here is very simple: instead of letting the current increase or decrease randomly, you control it like driving a car on a narrow street. As soon as the current goes off-course, you immediately adjust it. It's controlled by electronic switches (such as IGBTs or MOSFETs) that open and close rapidly depending on the current.The result is that the current remains almost constant, and the torque generated by the motor is constant, resulting in stable and smooth speed.

1.3 Applications

1. Electric Vehicles (EVs):

It is increasingly being used in automobiles because it can withstand heat and doesn't require permanent magnets (which reduces costs and reduces reliance on rare metals).

Excellent performance at high speeds.

2. Hybrid Vehicles:

Used for its efficiency and durability.

3. Drones and small electric aircraft:

Its light weight and simplicity help reduce the weight of the overall system.

4. Industrial Pumps and Fans:

Suitable for areas requiring reliability and high control speed.

5. Robotics and Automation Systems:

Because it precisely controls torque and operates in harsh industrial environments.

6. Washing Machines and Vacuum Cleaners:

In modern home appliances, especially those requiring high efficiency and variable speed.

7. Renewable Energy Systems:
such as small wind turbines or energy storage systems.

1.4 ABSTRACT:

The inductance of phase winding of a Switched Reluctance Motor (SRM) is a function of rotor position (θ) and current (i). An accurate dynamic model is required to predict the performance of the drive. In linear analysis, the inductance of the winding is assumed to be a function of rotor position only, as magnetic saturation is neglected. This paper deals with the linear model of the SRM. The linear model of the SRM drive is simulated with Hysteresis Current Control in MATLAB/SIMULINK [5].

1.5 Objective of this project

1.Understand the characteristics and operation of an SRM motor in terms of its construction, operation, and the differences between it and other types of motors.

2. Design a hysteretic current controller to control the motor's input current and maintain it within specified limits.

3. Stabilize the motor's speed using a control loop that feeds the necessary signals to the controller.

4. Implement a simulation using MATLAB/Simulink to test the system's performance and analyze the results.

5. Study the impact of the proposed control method on overall performance in terms of stability, response, and ripple reduction.

CHAPTER TWO

SWITCH RELUCTANCE MOTOR WITH CONTROLLER

Chapter two: Switch Reluctance Motor With Controller

2.1 Introduction

Variable reluctance motors (SRMs) are classified based on their geometric specifications and the number of stator and rotor poles. Figure (1) shows a cross-section of a three-phase, SRM motor with 6 stator poles and 4 rotor poles. [6]

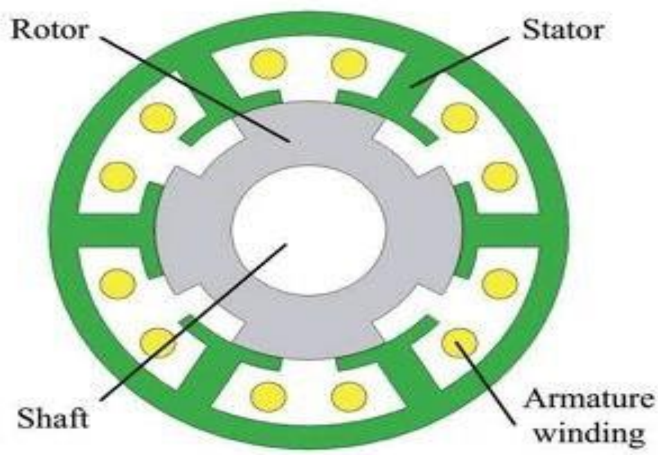


Figure 1. Three-Phase 6/4 SRM

In SRM, The applied voltage to a phase is equal to the sum of the resistive voltage drop and the rate of change of flux linkages as
given below:

$$v = R_s i + \frac{d\psi(\theta, i)}{dt} \rightarrow equation(1)$$

Where Rs is the Stator Resistance per Phase and is Flux Linkage per Phase.

$$\psi = L(\theta, i)\, i \rightarrow equation(2)$$

Where, Lis the inductance depends upon the rotor position as well as the phase current. Phase Voltage equations.

2.2 Characteristic of SRM

The rotor is basically a piece of steel (and laminations) shaped to form salient poles. So it is the only motor type with salient poles in both the rotor and stator. The number of poles on the SRM’s stator is usually unequal to the number of the rotor to avoid the possibility of the rotor being in a state where it cannot produce initial torque, which occurs when all the rotor poles are aligned with the stator poles. These phase windings can be excited separately or together depending on the control scheme or converter. Due to the simple motor construction, an SRM requires a simple converter and it is simple to control.

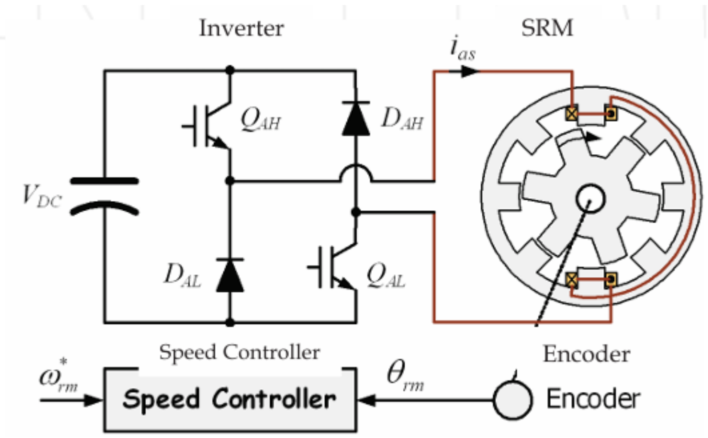
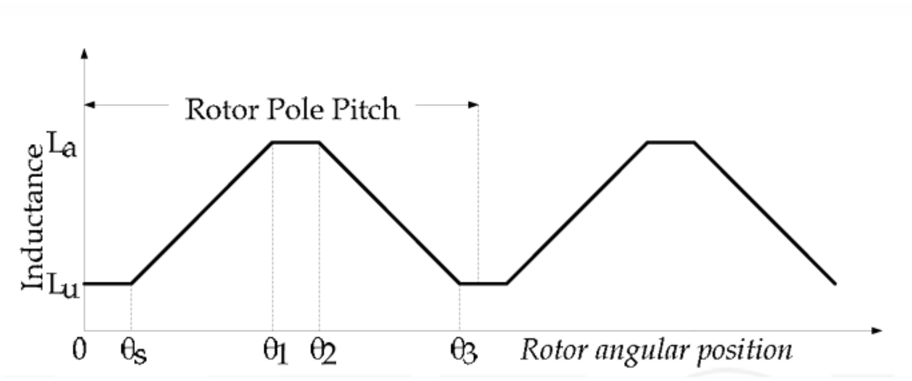


Fig2. SRM with one phase asymmetric inverter

The aligned position of a phase is defined to be the situation when the stator and rotor poles of the phase are perfectly aligned with each other (θ1-θ2), attaining the minimum reluctance position and at this position phase inductance is maximum (La). The phase inductance decreases gradually as the rotor poles move away from the aligned position in either direction. When the rotor poles are symmetrically misaligned with the stator poles of a phase (θ3-θs), the position is said to be the unaligned position and at this position the phase has minimum inductance (Lu).



The relationship between inductance and torque production according to rotor position is shown in Fig. 3

2.3 i-Hysteresis Current Control

Themost classical and easiness implemented controller is the hysteresis. The only control parameter is the hysteresis bandΔH. In the case of an analog implementation, this parameter ensures that the instantaneous current isbounded between $i*\pm\Delta H/2$, where $i*$ is the desired current. In this case, thecurrent ripple isequal toΔHand thecurrent controller output takesonly two distinct values ±Udc . The two main drawbacks of this controller are the increase of the current ripples at steady state and the production of avariable switching frequency ,which generate additional acoustic noise in SRM.To reduce these ripples, the hysteresis band ΔH must be reduced but it increase the switching frequency of the converter, and therefore increase thepower converter losses. However, inpractice, the current controller is implemented on aprocessor.To reduce these ripples as much as possible,the sample time Ts must be small.Therefore, this latter is limited. At lower speeds, the motor back-EMF is small compared to the supply voltage and the current flowing through the stator winding can be regulated by current chopping. So current control method is applied to low and medium speeds [6, 7, 8]. The block diagram of Hysteresis Current Control

is shown in Fig. 4. The actual speed is compared with the reference speed and error is given to a PI controller, which outputs reference current. The commutation controller takes the position sensor signal and decides which phase is to be switched On. The inputs to the Hysteresis Current Control block are reference current, actual current, θon and θoff .When the current exceeds a specified set-point value iH, controller turns Off two switches in a phase leg of the converter to regulate the current. Switches are turned On again when the current falls below a second level iL= iH - Δi, where Δi is the hysteresis band [9].

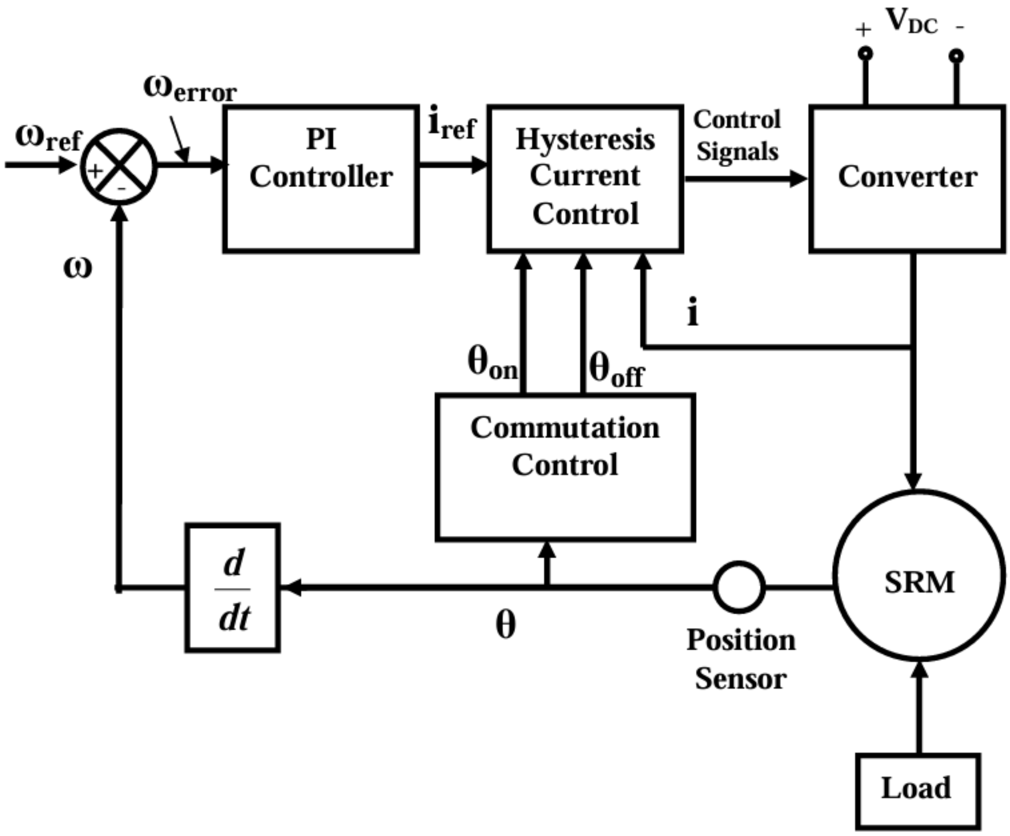


Fig.4 Block diagram of Hysteresis Current Control

ii-Principle Of Hysteresis Current Control

This strategy is preferable over wide speed range for SRM operation because the desired current can be easily reached. The control strategy based on turning on the switches of the converter when the phase current is lower than a lower band limit, and turning off these switches when the current is above an upper band limit [10,11]. The lower limit and the upper limit can be obtained according to the control requirements and the switching frequency of the power converter of SRM [13].

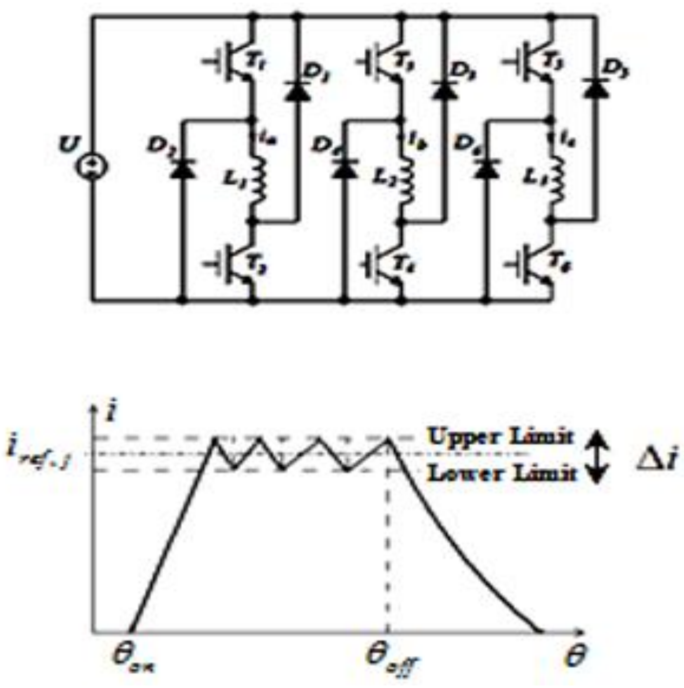


Fig.5 Converter and hysteresis band

2.4 PI Control

In a switch reluctance motor (SRM)The primary goal sometimes isn't just to generate torque, but to keep the motor running at a specific speed we require (for example, 1,500 rpm), regardless of external loads trying to slow it down. This is where the PI controller comes in as a regulator that controls the motor speed as follows:

It calculates the error between the reference speed and the actual speed.

Error (e) = $\omega\_ref - \omega\_actual$

The PI controller receives this error. The proportional part multiplies the current error by a constant coefficient and quickly attempts to correct it.The integral part adds the error over time and processes it, even if the error is small but persistent, which is ignored.

$u(t) = Kp \times e(t) + Ki \times \int e(t)dt$

Kp = proportional gain constant

Ki = integral gain constant

u(t) = the required current or torque control signal for the motor.

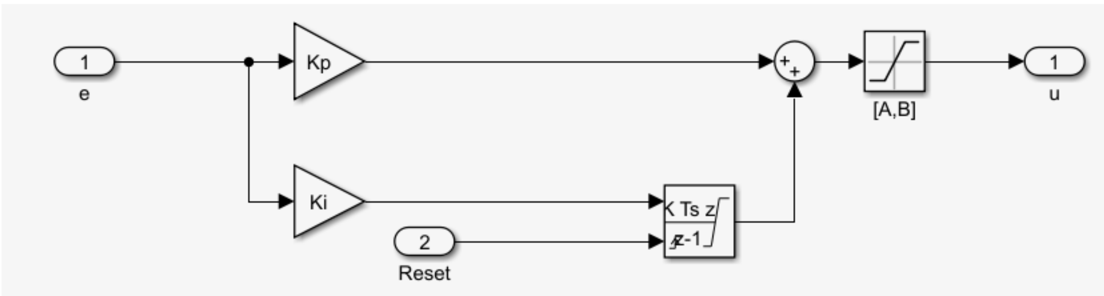


Fig.6 PI Control of SRM

CHAPTER THREE

SIMULATION AND ANALYSIS OF HYSTERESIS CURRENT CONTROL OF SRM

Chapter Three

SIMULATION AND ANALYSIS OF HYSTERESIS CURRENT CONTROL OF SRM

3.1 Introduction

The applications of SRM drive applications have increased in recent years because of advantages such as simple construction and low manufacturing cost. The main drawback of the motor is that it because of non-linear magnetic characteristics high torque ripple is high, which causes noise and vibrations [9,13].A dynamic simulation of the drive system enables verification of the analytical designs and the ability of the motor drive system to match the load torque over its entire speed range both in its steady state and during transients. With such verification, time and cost of the product development are minimized by avoiding a trial-and-error approach to prototype construction that may lead to repetitive testing and redesign until specifications are met. Simulation of the drive system requires accurate models for SRM drive systems. Investigating the operational behavior of the SRM requires mathematical model. Many different models and possible ways of modeling SRMs have been developed and published in the literature [14]. The phase inductance or flux-linkage is a non-linear function of rotor position and stator current. In linear analysis, neglecting the magnetic saturation the phase inductance depends only on the rotor position. Linear modeling of SRM has been presented by F.Soares et al. [15]. In this paper, the effect of varying turn-off angle on the torque ripple with two control strategies namely Hysteresis Current Control and Voltage Control is investigated. It has been concluded that, the torque ripple magnitude not only depends on the turn-off angle, but also on the motor speed and the load torque. The simulation results are compared with the experimental results, and found to be in close agreement with it. Linear model is simple, but inaccurate as it ignores the non-linear characteristics of the motor. This paper analyses the performance of Hysteresis Current Control of SRM using linear model.

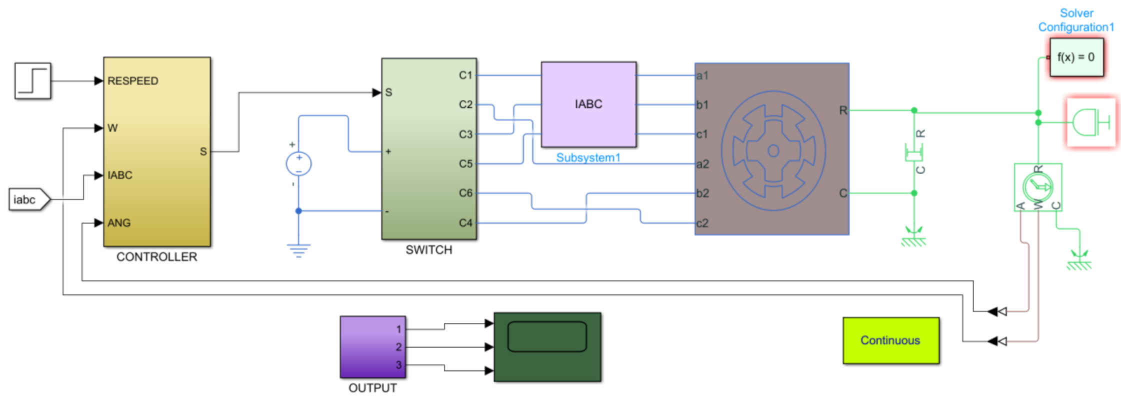


Fig7. Switched Reluctance Motor (SRM) Speed Control using a Hysteresis Current Controller.

3.2 Simulation of the 6/4 Model

a) Power Converter

The Switching Circuit is a critical part of the SRM(Switched Reluctance Motor) drive system. Its main role is to control the flow of current to themotor windings (phases A, B, and C) based on the control signals coming from the controller block.

1.Composition Of the Switching Circuit:

The circuit consists of six electronic switches of the IGBT type and 6 diodes are used to protect the circuit, These switches are controlled through gate signals generated by the controller, which are based on rotor position, reference speed, and current feedback.

2- Circuit working principle:

i.The controller calculates the exact timing for each phase to be energized based on the rotor angle and desired speed.

ii.It sends signals (S1 to S6) to the gate terminals of the IGBTs.

iii.When a pair of IGBTs is turned ON, current flows through the respective motor winding, creating a magnetic field that attracts the rotor teeth.

iv.As the rotor moves, the controller turns OFF the current in one phase and turns ON the next, creating continuous rotation.

3- Circuit benefit:

i.The SRM requires precise phase switching, unlike traditional motors.

ii.The use of 6 IGBTs allows independent control over each winding,

which is essential for accurate torque production and rotor positioning.

iii.It enables high-speed operation and dynamic response, which are

core objectives of SRM applications .

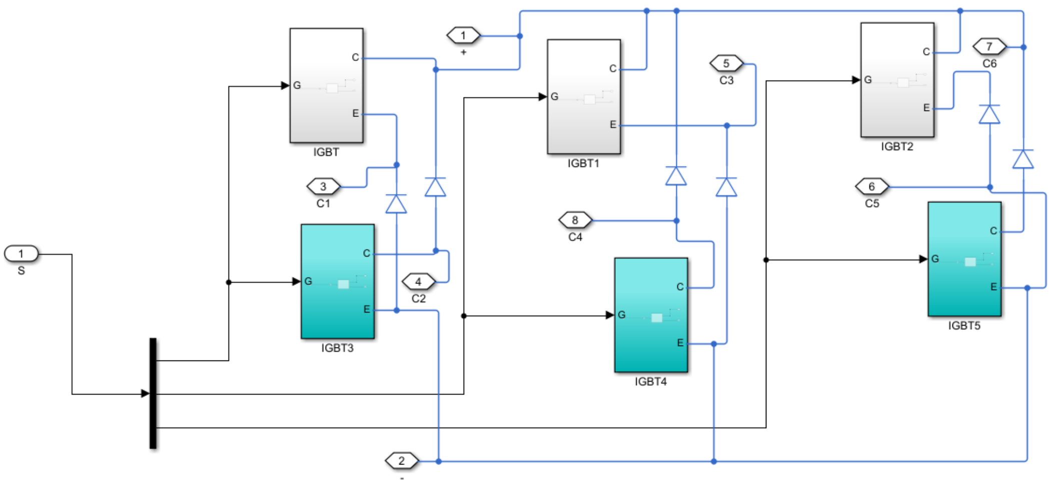


Fig8. Circuit Switch (Power Converter)

b) Position sensor:

ideal rotational motion sensor It's a block in a simulation environment, such as MATLAB's Simulink, whose purpose is to represent an idealized rotary motion sensor. This means:

It doesn't represent a real device itself, but it represents the ideal model of a sensor in simulating motors or mechanical systems.It has no delay, noise, or power loss.It is used only in simulations to track the rotation angle and rotational speed (angular velocity or RPM).

What is its purpose?

1. Monitoring rotor motion: We know where the rotor is at any given moment.
2. Measuring speed: We can determine whether the motor is fast or slow, and use this data in control systems (such as a PI controller).

3. Feedback:We use the ANG and RPM signals as feedback to manage and operate the motor efficiently, especially in position-dependent motors, such as variable reluctance motors or servo motors.

Why is it called "Ideal"?

Because it's an ideal model, with no errors or delays.

In real life, sensors may have:

- Measurement error.
- Time delay.
- Noise.
- Accuracy issues.

However, the model is used by the engineer to simplify the simulation and provide accurate and rapid results.

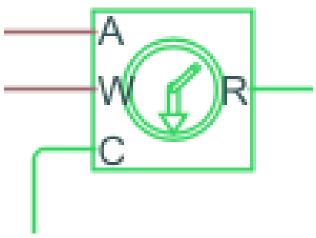


Fig9. Ideal Rotational Motion Sensor

3.3 Speed Control of SRM

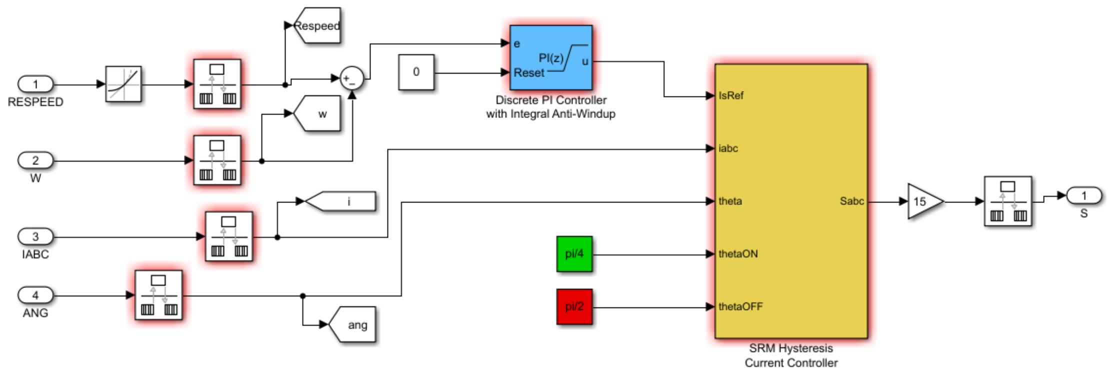


Fig10. Block Control

a) Proportional and Integral (PI) Controller

It is a control feedback mechanism used in various industrial control systems. The PI controller attempts to eliminate the error which is the difference between measured variable and desired value by adjusting the process inputs. The combination of proportional and integral terms is used to increase the speed of response and to eliminate the steady state error. The output response of proportional term is equal to the current value of error. The proportional factor is adjusted by multiplying the error value by a proportional gain which is denoted by KP. The integral term is proportional to both the magnitude and duration of the error. In PI controller, the integral term is the sum of instantaneous error over time which gives the accumulated value. Combining both terms, the relationship between the outputs from the controller to the error input is given by:

$$u(t) = Kp \times e(t) + Ki \times \int e(t)dt$$

The speed of SRM is controlled by PI controller. The controller has simplicity, lowest cost, zero steady state error, ease of implementation, good speed response and robustness. It is extensively used in AC and DC drives where speed control is required. In order to provide the desirable performance of SRM, feedback control system is employed for speed control of SRM drive. The tuned values of the PI controller constants are dependent on the system. [8]

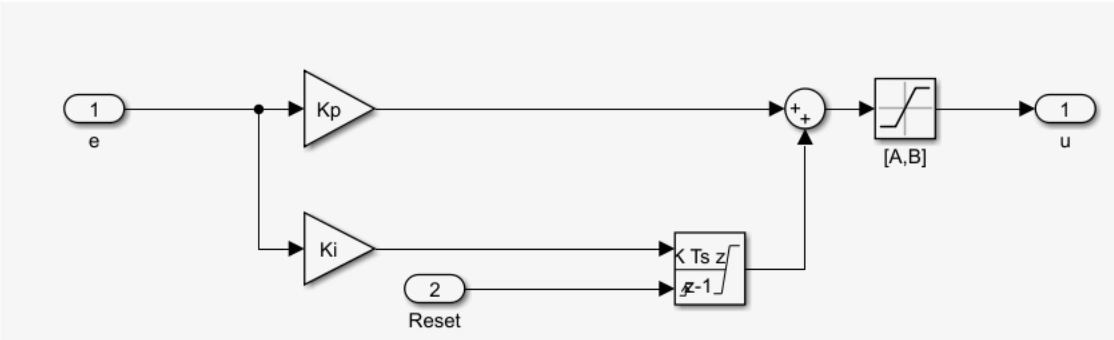


Fig11. Block PI Control

b) Hysteresis Current Controller

The most classical and easily implemented controller is the hysteresis controller with the hysteresis band Al to be the only controlling parameter. This parameter makes the instantaneous current to be bounded within a band around a reference value between", where is the desired current. The control is carried out by turning on the switches of the converter when the phase current is lower than a lower band limit, and turning off these switches when the current is above upper band The main objective of this circuit is to control the speed of a variable reluctance motor (SRM) using a digital PI controller and hysteresis current control technology. The current in each phase is adjusted based on the rotor position and on/off angles, ensuring efficient motor operation and reducing torque ripples. This type of control helps improve motor performance in applications that require fast response and high torque. These inputs are connected to a set of blocks that likely represent current sensors. Their function is to measure the actual current values flowing through the different phases of the motor (in this case, it looks like three phases represented by the signals iabc). These actual current values are essential information that the hysteresis controller needs to perform its function.

How it works (simplified):

The hysteresis controller operates based on the principle of comparing the actual current with the reference current for each phase. The controller determines the switching state of the power switches (such as transistors or thyristors) that supply the motor phases based on this comparison within a defined range called the Hysteresis Band.

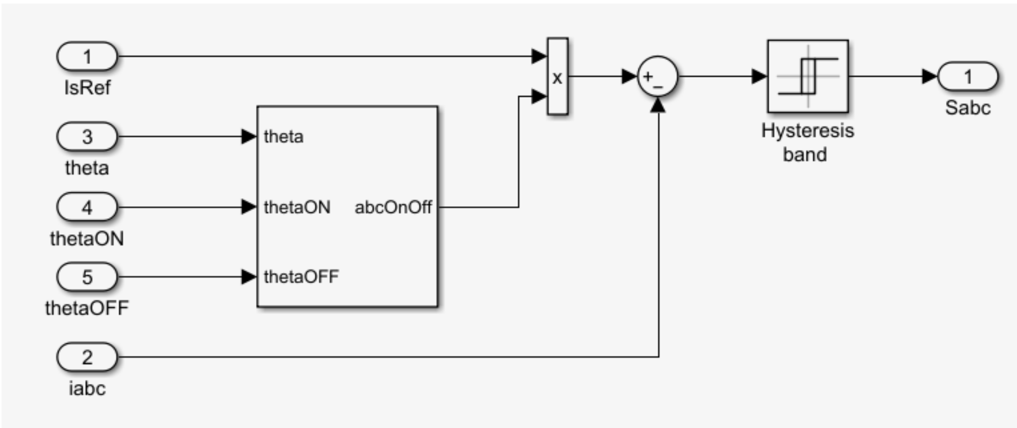


Fig12. Block Control Current Hysteresis

CHAPTER FOUR

Chapter Four

4.1 Introduction :

In this chapter, the performance results of the Switched Reluctance Motor (SRM) drive system are presented and critically analyzed. The simulation outcomes reflect the behavior of the motor under various control conditions and parameter settings, with particular focus on the output response characteristics such as current waveforms, torque profile, and speed regulation.The results serve as a practical validation of the theoretical models and control strategies discussed in previous chapters. Special attention is given to evaluating the dynamic response of the SRM, including the impact of tuning control parameters such as the proportional gain (Kp) and integral gain (Ki) within the PI controller. These parameters significantly influence the settling time, overshoot, and the quality of current regulation — all of which are critical for efficient and stable motor operation.Through graphical and numerical analysis, the effectiveness of the implemented control scheme is assessed under different load conditions and reference speeds. The results not only demonstrate the potential advantages of the SRM system but also highlight areas where performance can be optimized further.

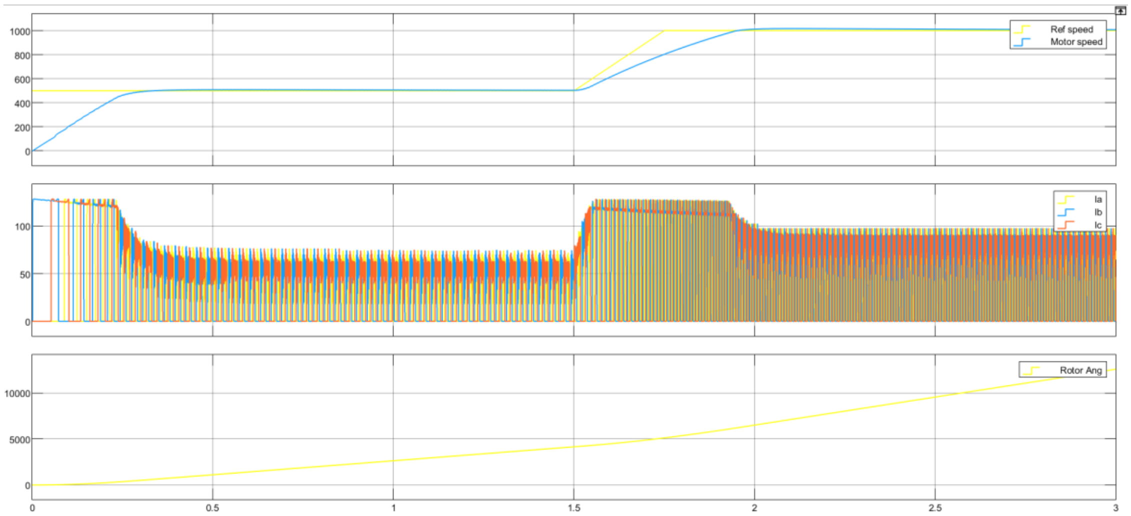


Fig13. (I) Output Ref speed and Motor speed. (II) Output 3phase inverter. (III) Output Rotor Ang.

- If KP =1 , KI=50

In this test case, the PI controller parameters were set to Kp = 1.0 and Ki = 50. The speed response, as illustrated in the top subplot, shows that the motor is capable of reaching the reference speed of 500 rpm with a relatively short rise time. However, a noticeable overshoot is observed, followed by a slight undershoot before the system stabilizes. The total settling time is approximately 0.6 seconds. This behavior indicates that the proportional gain (Kp) contributes effectively to the initial acceleration, but the relatively low integral gain (Ki) delays the elimination of steady-state error, thereby extending the time required for the system to fully settle. Additionally, oscillations are present both after the initial overshoot and during the transient phase. The absence of a derivative term in the controller likely contributes to the persistence of these oscillations, as the system lacks adequate damping to counteract rapid fluctuations.

The middle subplot, which displays the phase currents (Ia, Ib, Ic), reveals that the current waveforms are still far from ideal. The currents exhibit sharp, irregular pulses rather than smooth sinusoidal waveforms. This non-sinusoidal behavior reflects poor current shaping, which can be attributed to the insufficient integral action. While the chosen Kp value introduces acceptable responsiveness, the Ki value of 50 does not provide enough correction to minimize ripple or enforce harmonic smoothness across the three phases.In conclusion, while the speed control performance using Kp = 1.0 and Ki = 50 is relatively acceptable in terms of response time, the overshoot, oscillatory behavior, and highly distorted current waveforms indicate that further tuning is necessary. Increasing the Ki value is recommended to enhance the steady-state performance and improve the current waveform quality, bringing it closer to the desired sinusoidal Profile.

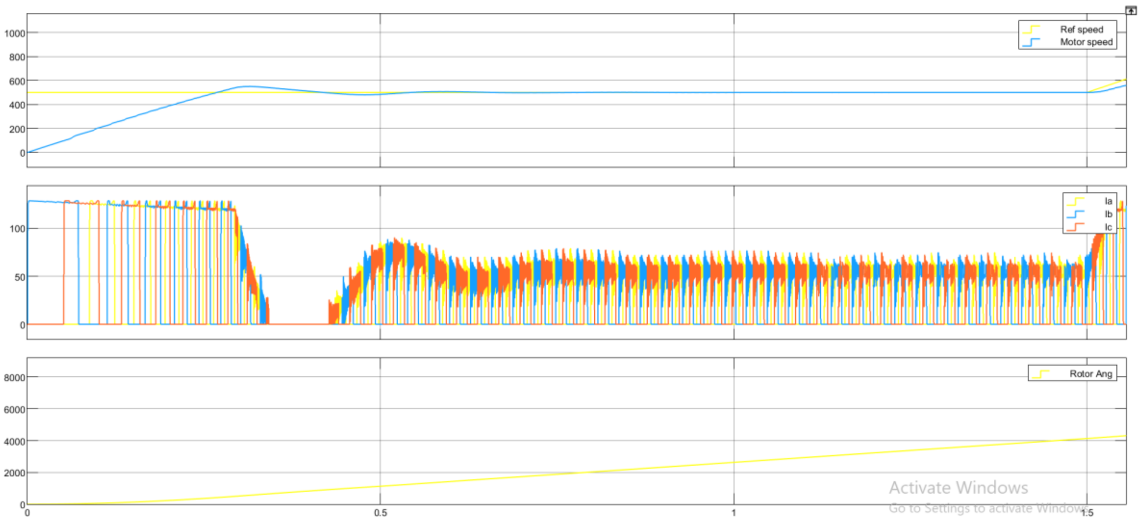


Fig14. Whan KP=1 , KI=50 (I) Output Ref speed and Motor speed. (II) Output 3phase inverter. (III) Output Rotor Ang.

- If KP=1 , KI=100

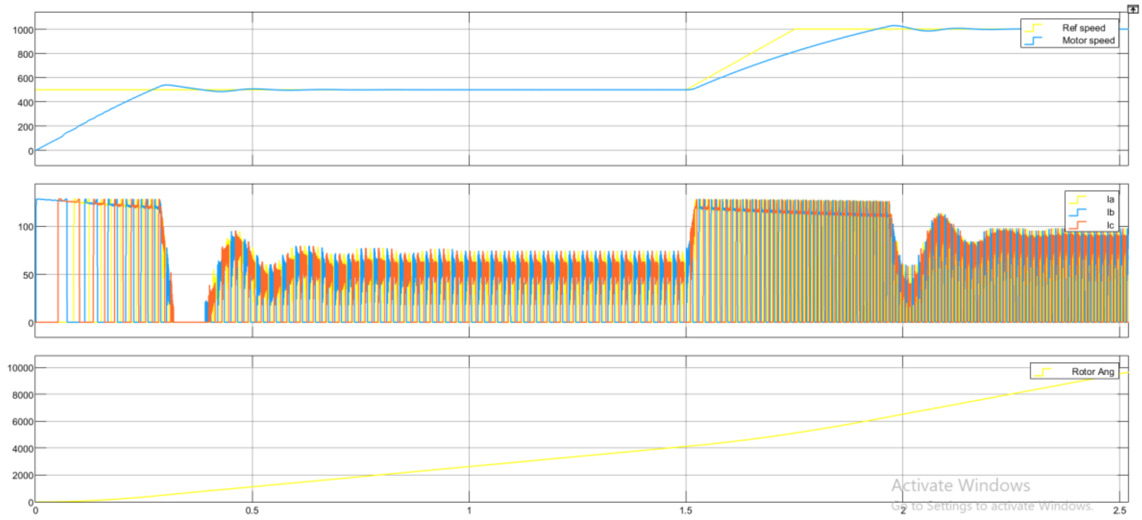


Fig15. Whan KP=1 , KI=100 (I) Output Ref speed and Motor speed.

(II) Output 3phase inverter. (III) Output Rotor Ang.

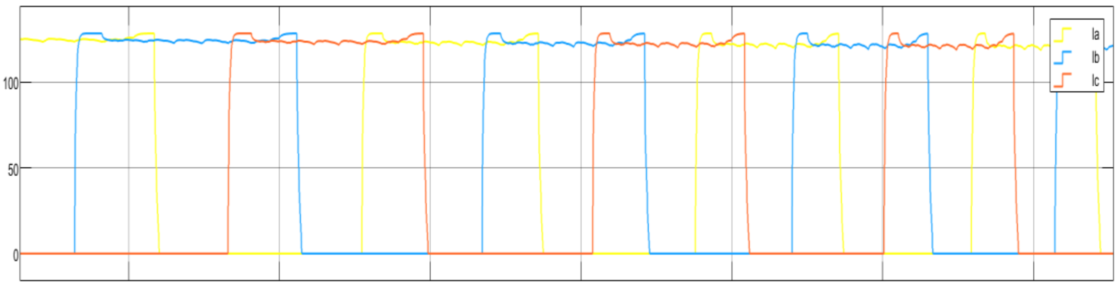


Fig16. When KP=1 , KI=100 Output 3phase inverter.

In this case, the PIC parameters were set at and to improve system response and reduce the reference speed tracking error. The results showed that increasing the integral value to 100 contributed to accelerating the gradual cancellation of the constant error, which positively impacted the settling time, as the motor speed approached the reference value within a shorter period of time compared to cases with lower values of and. However, a clear overshoot was observed in the resulting signal after the speed reached the reference value. This is attributed to the fact that the low value of the PIC was insufficient to prevent the signal from rising too rapidly after the reference change, leading to a significant overshoot in the speed response. In addition, the resulting signals exhibited clear oscillations after each speed change, resulting from poor damping in the system due to the high ratio between and, which reduced the overall dynamic stability of the system. As for the shape of the three-phase currents (Ia, Ib, Ic), they appeared more regular compared to the previous cases, but they still contained a significant amount of ripple, indicating that the current response has not yet reached the ideal sinusoidal shape required for high-performance applications. Therefore, while these current values offer a partial improvement in response speed, they still require improvement by gradually increasing the value to achieve a more balanced response between tracking speed, stability, and reducing ripple in the currents.

- If KP=30 , KI=100

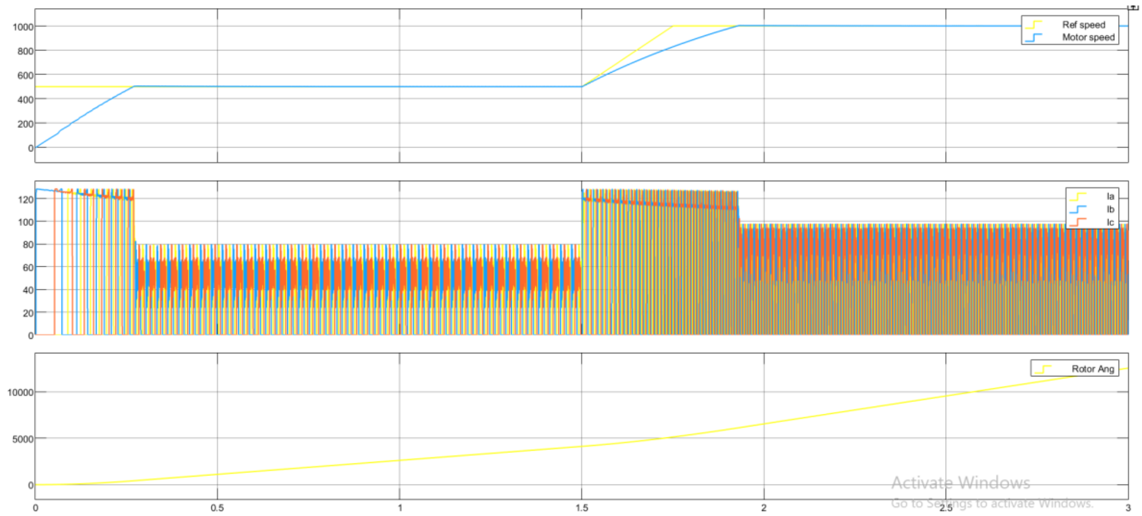


Fig17. Whan KP=30 , KI=100 (I) Output Ref speed and Motor speed.

(II) Output 3phase inverter. (III) Output Rotor Ang.

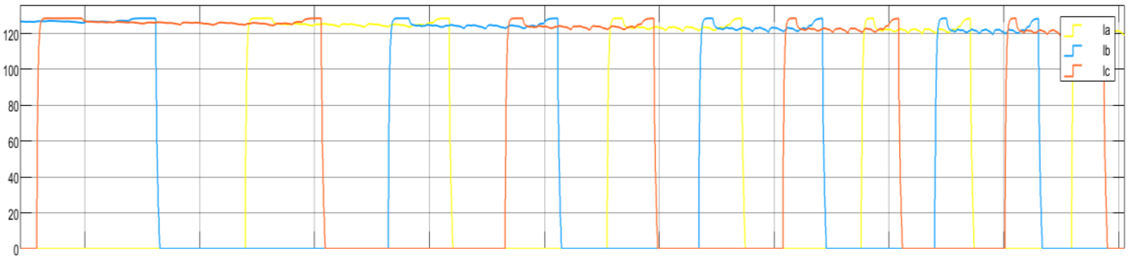


Fig18. When KP=30 , KI=100 Output 3phase inverter.

When using high values of the integral and proportional coefficients, such as ki equals 100 and kp equals 30, in a variable reluctance motor speed control system, some dynamic characteristics are clearly evident in the resulting speed and current signals. These values lead to a rapid response from the controller to any change or error in the reference speed, enabling the system to catch up to the desired value within a short period of time. However, this rapid behavior is often accompanied by a noticeable oscillation around the equilibrium point due to the aggressive nature of the corrected signals produced by the controller. This oscillation results from the system continuously attempting to correct the error without allowing sufficient time for stabilization between corrections.

On the other hand, overshoot is clearly evident as a result of the system's excessive response, where the actual speed exceeds the reference value before returning and decreasing towards it. This temporary increase in speed above the desired value is a direct result of the response force generated by the proportional-integral control amplifier, which in turn initially generates excessive torque. After the initial increase, the system begins to oscillate around the reference value until it gradually stabilizes.

In terms of its impact on currents, the resulting electrical waves are unsmooth and contain sharp, repetitive fluctuations due to the frequent activation and deactivation of electronic switches at high speeds to maintain the current within the hysteresis belt. These behaviors indicate a system characterized by rapid response and good tracking accuracy, but they require additional thermal management and control to mitigate the negative effects resulting from fluctuations and overshoot associated with high control parameter values.

CHAPTER FIVE

Chapter Five : Conclusion

5.1 conclusion

Efficiency, robust construction, speed-torque characteristics, and efficiency with high-speed operations make SRMs superior to other conventional motors in many applications. This paper presents a cascaded converter-fed SRM drive with reduced switching losses. The paper presents a simplified hysteresis current control (HCC) for cascaded converter-fed SRM. The simplified HCC control method reduces switching losses as HCC is applied to only one bridge of the cascaded converter. Although the performance of the SRM remains the same as with cascaded converter-fed SRMs with HCC applied to only one bridge or to two bridges and with conventional asymmetrical converters, the switching losses are reduced to a great extent when HCC is applied to one bridge of the cascaded converter-fed SRM. When HCC drives only the upper switches of the converter, multiple turns ON and OFF per cycle are observed in only the upper switch, while the lower switch continuously turns ON or OFF, and the switching losses in the cascaded converter decrease when compared to HCC driving both bridges. The 6/4 switched reluctance motor is driven by asymmetric bridge converter and it has simpleconstruction and control compared to a commutation motor. The SRM was modeled on Simulink and simulated for best performance. The PI controller gave the best result in terms of reduction of settling time, elimination of speed overshoot and steady-state error.

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