Minimizing Torque ripple of SRM using Nonlinear MPC based Controller

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Abstract - *The Switched Reluctance Motor is an old member of the electric machine family. It receives the significant response from industries in the last decade because of its simple structure, ruggedness, high reliability, inexpensive manufacturing capability and high torque to- mass ratio. The Switched Reluctance Motor consists a salient pole stator with concentrated coil and salient pole rotor, which have no conductors and magnets. The motor's doubly salient structure makes its magnetic characteristics highly nonlinear. This work briefly describes the constructional features, principle of operation and mathematical model of Switched Reluctance Motor. However the application of SRM has been limited because of their large torque ripple, which produces noise and vibration in the motor. In order to solve these problems, MPC based Instantaneous Direct Torque control (IDTC) technique is used in order to control the torque of the Switched Reluctance Motor. By using this method we can well regulate the torque output of the motor with I hysteresis band. The PI controller achieves closed loop speed control operation.*

Key Words: IDTC, MODEL PREDICTIVE CONTROL, HYSTERESIS BAND, PI CONTROLER, CLOSED LOOP CONTROL

1. INTRODUCTION

1.1 Switched Reluctance Motor

The switched reluctance motor has been used in many commercially adjustable speed applications due to its unique mechanical structure and simple power electronic drive requirements. The intrinsic simplicity and ruggedness make it superior to other electric machines. Because unidirectional current is required from the converter, only one switch per phase is needed. Even though some converters use more than one switches to increase the reliability or to realize certain control strategies that are not possible by using only one switch per phase. In addition, each phase winding of the SRM is independent; so, it can operate with some of the phase windings disabled, at a lower power output.

However, the SRM is suffered from noticeable torque ripple and audible noises that prevent it from used in high performance drives. The torque ripple in the SRM is induced due to highly non-linear and discrete nature of the torque production mechanism, which is significant at the commutation instant. Hysteresis current controller, as a traditional open-loop current control scheme for SRM, bringsit large acoustic noises due to the varying switching frequency.

In the past, several control schemes have been suggested for torque ripple and noise reduction. However, most of these prior arts have been focused on motor design, converter topology and modulation strategy [1 – 4]. Although there are some modeling methods for the SRM drives developed [5 – 8], they do not present rigorous mathematical formulation of the system operation behavior due to the high degree of non-linearity in SRM circuit. Therefore, the conventional closed-loop pulse-width-modulation current controller needs to be designed with non-linear control techniques that do not involve the motor and converter modeling or with the open-loop Hysteresis controller that needs to vary the switching frequency to maintain constant Hysteresis current band, resulting unpleasant audible noises.

Although the PWM current controller has been proposed and proven to be effective in the noise reduction [9], without knowing the transfer function, it is difficult to design the controller with proper gains and bandwidth to maintain system stable. In this thesis, the ac small signal modeling technique is proposed for linearization of the SRM model, and a conventional PI controller is designed accordingly for PWM current controller. Fig.-1 shows the proposed SRM drive system with PWM current feedback loop.

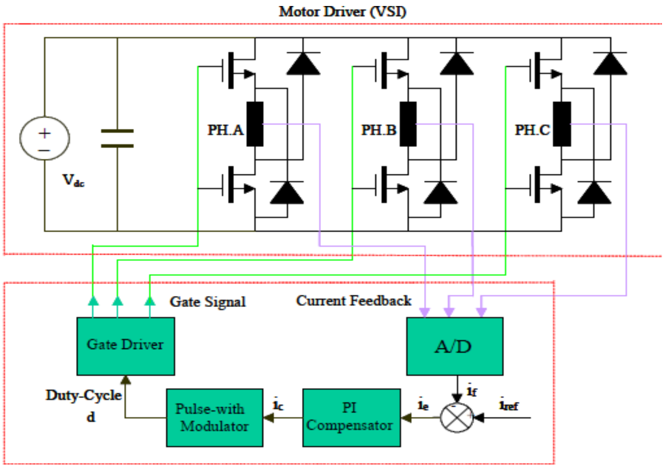


Fig - 1 SRM drive system with the current feedback loop

1.2 AC SMALL SIGNAL MODEL IN SRM

Ac small signal modeling technique is usually used as a tool to analyze the non-linear dynamic system. By perturbing and linearizing the averaged waveform (over one switching cycle) about a quiescent operation point, ac small signal model of the system can be obtained. Because it is a linear model, it can be solved using conventional analysis techniques to obtain the system small signal transform function, output impedance and other frequency dependent properties. As a result, engineers can gain insight to the system operating behavior, both the time-domain and phase-plane trajectory.

In order to design the feedback controller shown in Fig - 1, an ac small signal model of the entire system is needed. With the ac small signal model, the controller can be designed to meet the specifications such as stability, transient overshoot, settling time, and steady-state regulation by adjusting the controller parameters. AC small signal modeling technique has been widely used in power converters for many years. However, for the industrial drives, especially for the SRM, the work has not been explored. The purpose of this work is to propose a linearized ac small signal model for the SRM control system shown in Fig - 1. This model is based on the state-space analysis for the pulse-width modulated converter and current-mode control feedback circuit. The goal of this model is to develop a duty cycle modulated current controller suitable for the SRM drives. Fig - 2 shows block diagram of the proposed SRM drives with current feedback system derived from the ac small signal model.

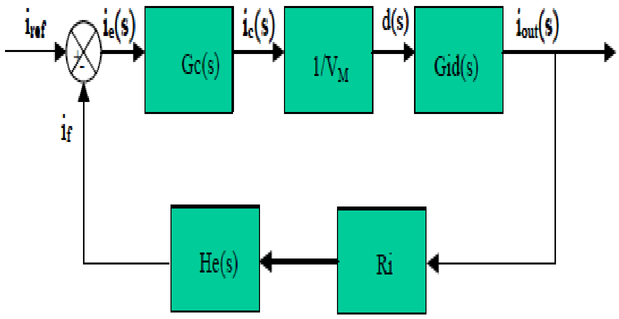


Fig - 2 Block diagram of the SRM drive with current feedback system

In the proposed SRM drive system shown in Fig - 1, two-quadrant-chopping converter and PI compensator are used. Usually, current control techniques for the two-quadrant-chopping converter can be classified into non-linear and linear control. For the SRM, traditionally, nonlinear current controllers that are based on Hysteresis strategies are used. With this control scheme, the measured phase current is directly compared to the Hysteresis band to create switching gate signal for the two-quadrant-chopping converter. The Hysteresis method was preferred due to easyimplementation and fast dynamic response. However, it operates in widely varyingswitching frequencies with large current ripple; also, it is a kind of open-loop control, resulting poor dynamic response. In this project, a linear current control scheme, or synchronous PWM PI controller, is proposed. The PI controller integrates the error between the feedback and reference current to generate a variable voltage value; then, this value is fed into a triangle pulse-width Modulator to produce gate signal for the two-quadrant-chopping converter. Compared totraditional Hysteresis controller, the PWM PI controller has demonstrated some advantages: 1) constant switching frequency; 2) closed-loop control; 3) smallcurrent ripple; 4) low acoustic noise. PI controller has been widely used in all types of the feedback system especially for the system with a single pole.

1.3 THESIS OBJECTIVE

In this project, the ac small signal modeling technique will be proposed for linearization of the SRM model such that a conventional PI controller can be designed accordingly for PWM current controller. With the linearized SRM model,the duty-cycle to output transfer function can be derived, and the controller can be designed with sufficient stability margin. Also, the proposed PWM controller will be simulated to compare the performance against the conventional controller based system. It can be found that through the frequency spectrum analysis, the noise spectra in audible range disappears with the fixed switching frequency PWM controller, but is pronounced with the conventional current controller.

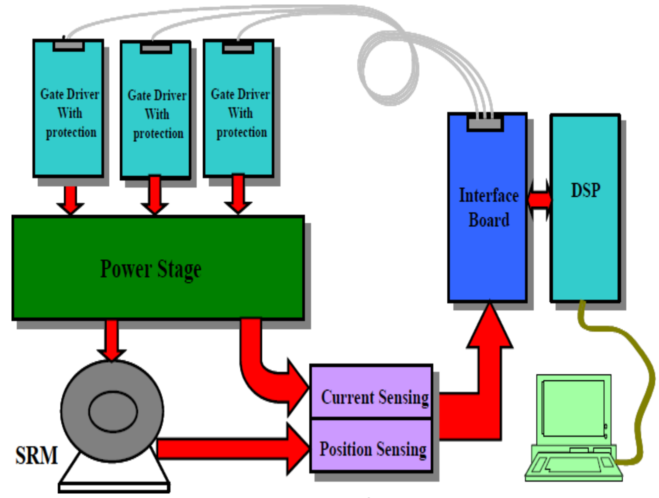


Fig - 3 Test bench for the SRM current control system

The test bench for SRM current control system is drawn in Fig - 3, which iscomposed of four blocks. The first block is the DSP controller, which samples the phase current feedback and the encoded position signal to produce six independent gate signals for the two-quadrant-chopping converter. This controller can realize the PI and pulse-width modulator function. The second block is the interface board. Onefunction of this block is to use three Hall current sensors to detect the three-phase currents respectively and convert them into voltage values, which are available for the DSP A/D converter. Another function of this block is to sense the encoded position signal and feed it to the encoder interface unit of the DSP. The encoded position signal is used to determine the timing to excite the switches on each phase. The third block contains gate drive boards, which amplify three-phase gate signalsproduced by the DSP controller to drive the power stage. The gate drive board provides the de-saturation protection signal through optical fiber to interface board.The fourth block is the power stage, which provides current to each phase windingto produce desired torque for the SRM.

The whole system developed is based on a half horsepower, three-phase SRM, which is used for the commercial washing machine. Also, the two-quadrant-chopping converter is used for the SRM drive.

2. METHODOLOGY (Hysteresis current control based minimization oftorque ripple in switched reluctance motor)

2.1 PROPOSED SYSTEM

As traditional control schemes, open-loop Hysteresis and closed-loop pulse- width-modulation (PWM) have been used for the switched reluctance motor (SRM) current controller. The Hysteresis controller induces large unpleasant audible noises because it needs to vary the switching frequency to maintain constant Hysteresis current band. In contract, the PWM controller is very quiet but difficult to design proper gains and control bandwidth due to the nonlinear nature of the SRM. In thisproject, the ac small signal modeling technique is proposed for linearization of the SRM model such that a conventional PI controller can be designed accordingly for the PWM current controller. With the linearized SRM model, the duty-cycle to output transfer function can be derived, and the controller can be designed with sufficient stability margins. The proposed hysteresis PWM controller has been simulated to compare the performance against the conventional peak to peakcontroller based system. It was found that through the frequency spectrum analysis,the noise spectra in audible range disappeared with the fixed switching frequency PWM controller, but was pronounced with the conventional average and peak to peak current controller. The PI controller is used to reduce the speed error and make the motor speed as constant with irrespective of the load.

This project presents a control technique for torque ripple minimization in the switched reluctance motor (SRM) drive, based on a torque-sharing function (TSF) concept. In the proposed method, the reference torque is directly translated into the reference current waveform using the analytical expression. Optimization criteria of a TSF that are concerned with secondary objectives, such as minimization of copper losses or maximization of drive performance, are described. In addition, a novel family of TSFs is introduced. An optimal TSF can be easily extracted fromthe proposed family to satisfy one of the secondary objectives or to create balance between more of them.

Control performances of the two extracted TSFs and the twooptimized conventional (linear and sinusoidal) TSFs are compared. These four TSFs keep the copper losses to nearly the theoretical minimum. Each of them provides approximately the same operation efficiency of the considered three-phase 8/6 SRM drive. However, due to extension of the commutation angle between adjacent phases, TSFs from the proposed family provide better torque-speed characteristics. Moreover, one of them expands the possible speed range of torque-ripple-free driveoperation, and another one, which provides the best torque speed characteristics, reduces the peak phase current.

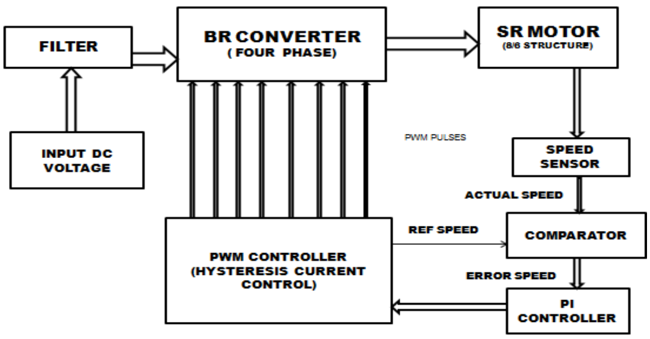
2.2 INTRODUCTION

The Switched reluctance motor (SRM), due to its simple structure and robust construction, has many advantages over other dc or ac machines. In contrast, one of the main disadvantages of SRM, especially for use in servo-type applications, is high torque ripple. The torque ripple is a consequence of the nonlinear torque- current-angle (T-i-θ) characteristics of SRM and the discrete nature of torque production mechanism. As SRM has the doubly salient structure, the torque ripple is particularly enhanced at the commutation instants when torque production is being transferred from one active phase to another. Many investigations have been undertaken over the past few decades in order to reduce torque ripple by applying the various techniques of the instantaneous torque control [3]–[16]. A convenient control approach is to coordinate the torque production of the individual phases so that the total torque tracks the reference value [3]–[8]. The instantaneous torque ofindividual phases is defined through the suitable torque-sharing function (TSF). Then, if the *T-i-θ* characteristics are available, the reference phase current waveformcan be derived according to the predefined torque waveform. Many TSFs can be specified to provide ideally torque sharing between individual phases and, thereby, to meet the primary objective of low torque ripple. Some of the commonly used TSFs are based on linear, sinusoidal, cubic, or exponential curves [3]–[8]. However, in order to select an optimal TSF and to optimize its parameters, it is necessary to specify a secondary objective. As any phase torque waveform can be translated into current or flux-linkage waveforms, the choice of TSF directly affects the copper losses and feeding voltage required to "track" the TSF.

Thus, the secondary objective may be minimization of the copper losses, minimization of the phase voltage or minimization of the peak phase current that are related to the drive efficiency, torque-speed capability, and peak current requirement for the power converter, respectively. Significant efforts to optimize TSF according to one of the aforementioned secondary objectives were made. In cases where more than one secondary objective is considered, deriving the optimal TSF becomes more complicated, as it dynamically changes. For example, minimization of the copper losses implies the fast commutation between neighbor phases (that is possible at low speed), but minimization of the phase voltage (that isrequired at higher speed to avoid voltage saturation) implies the expanded commutation period. In the most popular control approaches for torque-ripple minimization, the static *T-i-θ* characteristics are stored in 3-D lookup tables. During the motor operation, these data are used to determine the command current for eachphase from the information of the rotor position and the torque requirement. A preferable alternative is to calculate the command current by employing an analytical SRM model, but the implementation is mainly limited due to the insufficient model accuracy, model complexity and, in particular, inability toexpress the phase current as a function of torque and rotor position. The last of theseproblems can be overcome by applying the direct instantaneous torque control (DITC) scheme. DITC has simple structure but, on the other hand, its implementation implies the complex switching rules, uncontrolled switching frequency, and high sampling rate. The optimization criteria of TSF for torque- ripple reduction in SRM, providing the low copper losses with acceptable drive performance, are discussed in this paper. The novel, well adapted to the low copper losses, family of TSFs is proposed. Each TSF from the family provides that the phase currents flow through the whole region where positive torque production is possible. Thus, due to the expansion of commutation region, the torque-speed capability is improved, but copper loses still can be kept close to the theoretical minimum.

The TSF that makes the balance between more secondary objectives, such asdrive efficiency, torque-speed capability, or peak current requirement, can bechosen from the family. The procedure for extracting the optimal TSF that maximizes the possible torque-ripple-free speed range or that minimizes the magnetization voltage requirement is demonstrated through the considered examples. In the performed optimization, the saturation effects of magnetic field are neglected for simplicity sake, but the nonlinear characteristics of SRM are included in the calculations of current waveforms. Moreover, the reference current waveforms are directly derived from the reference torque by using the reliable analytical expression. Two TFSs from the proposed family and two conventional (sinusoidal and linear) TSFs are optimized for the considered three-phase SRM drive, and then their control performances are compared through the torque-ripple control applications.

Fig - 4 Proposed system block diagram



2.3 TORQUE SHARING FUNCTION

The input torque command *T* is divided into individual torque references for each phase through TSF function block with respect to the rotor position. The separate torque references are converted into current command signals in the"Torque-to-Current" block based on the rotor position information. The command currents are regulated through the hysteresis current controller. Alternatively, the "Torque-to-Flux" block and the flux controller can be used [8]. The reference phasetorque *T k* of each phase is obtained by proper shifting of TSF. TSF is divided intothe regions with zero and nonzero value s.

The nonzero region of TSF is divided into the sub region, where the considered phase *k* alone should develop the whole torque (*T k* = *T*), and the sub regions (called the commutation or overlap regions) where it shares the torque with one or more phases (0 < *T k* < *T*). In this paper, simultaneous excitation of no more than two phases in overlap region will be considered, since that is the condition anyphase in most of three-phase and four-phase SRMs does not produce negative torque.

2.4 PROPOSED SYSTEM CIRCUIT DIAGRAM

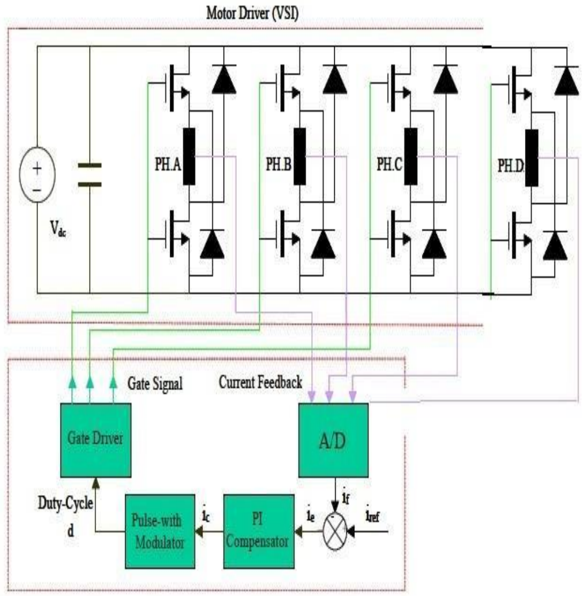


Fig - 5 Proposed system circuit diagram

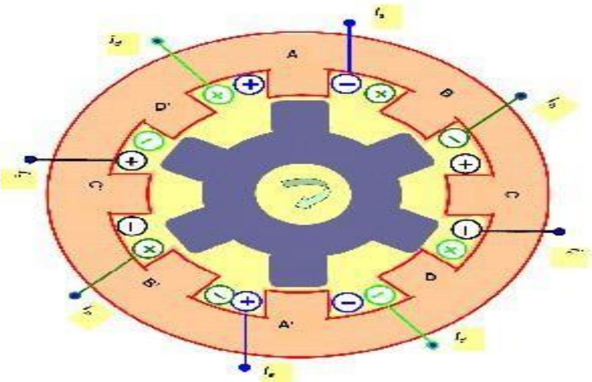


Fig – 6 8/6 SR motor structure

2.5 HYSTERESIS CURRENT CONTROL BLOCK

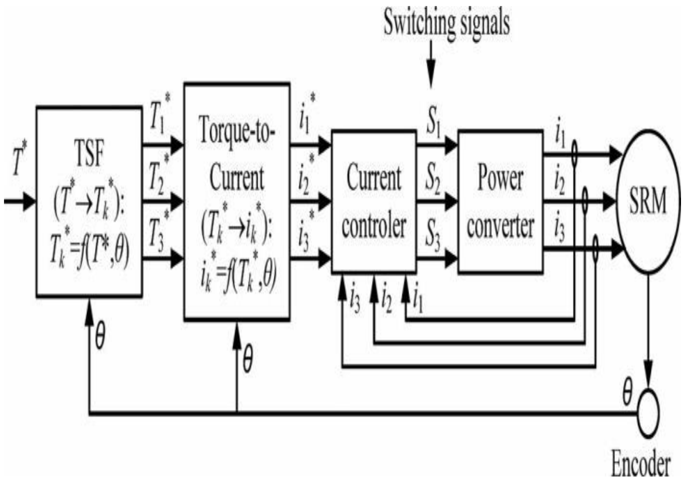


Fig – 7 Hysteresis current controller based SR motor block diagram

2.6 PROPOSED SYSTEM WORKING

The input AC voltage source is converter into a DC voltage using the singlephase diode bridge rectifier, and then this DC voltage is given to the SPLIT RAIL CONVERTER. This converter will convert the Dc voltage into the variable AC voltage according to the position sensor signals from the SR motor. From the position sensor signals we can get the actual speed of the SR motor, the four individual phase currents are sensed using the current sensor, these currents are saidto be actual current of the SR motor. The total torque of the SR motor is fed to the torque sharing function block, it will convert the total torque into the individual phase torques, then this torque is extracted and the equivalent current and flux wascalculated, this current is the reference current.

The reference current and the actual currents are compared by using the hysteresis current controller and the error is multiplied with the PI controller and PWM pulses were produced and these pulses are fed to the Split rail converter switches. The hysteresis current controller will reduce the current ripples, similarlythe reference and actual speeds are compared and the error is given to the PI controller this will reduce the Speed error and the motor will run at constant speed with different loads. That means the PI controller will make the voltage to the SR motor is constant by varying the width of the PWM pulses and voltage to the motor is constant. If the current is increased means the hysteresis current controller will increase the width of the PWM pulses to the Split rail converter, So that the voltageto the motor has increased and current will be reduced. Hence because of this reduction in current the torque ripples in the SR motor was reduced.

3. DISCUSSION

3.1 PROPOSED SYSTEM SIMULINK

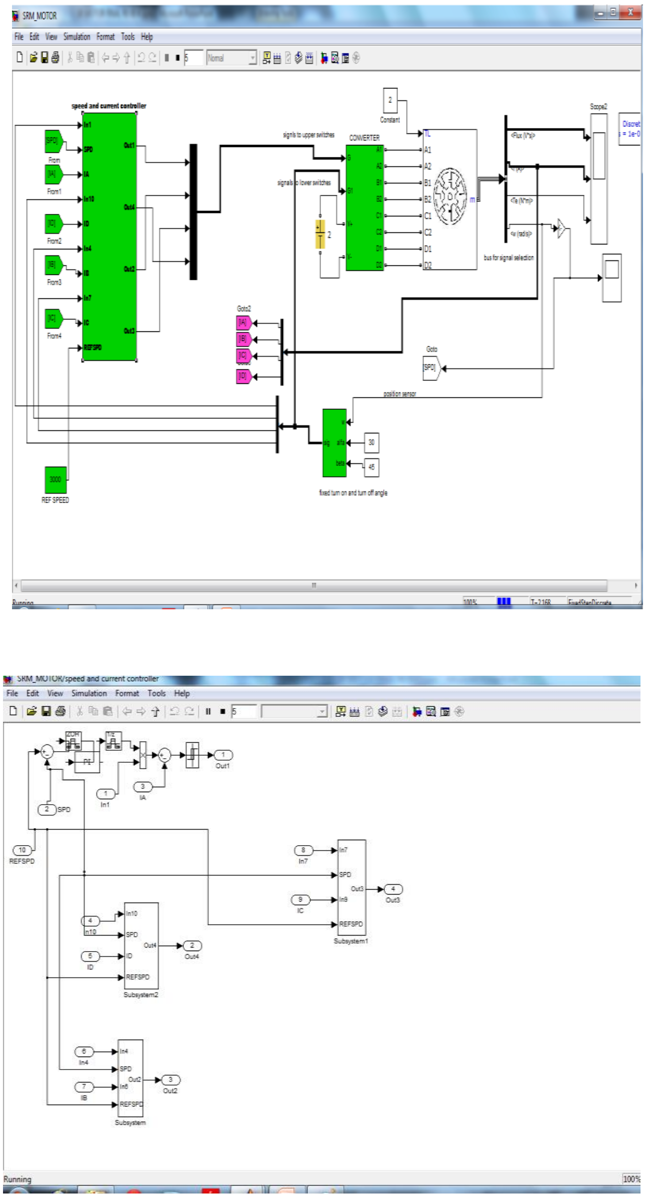


Fig - 8 Proposed system matlab Simulink

3.2 PROPOSED SYSTEM PWM PULSES TO THE CONVERTER

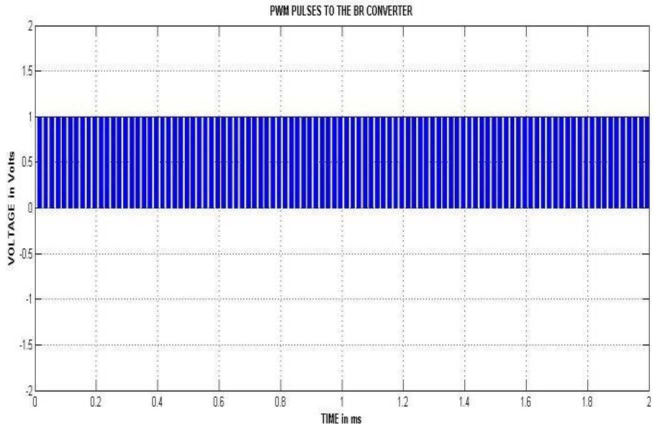
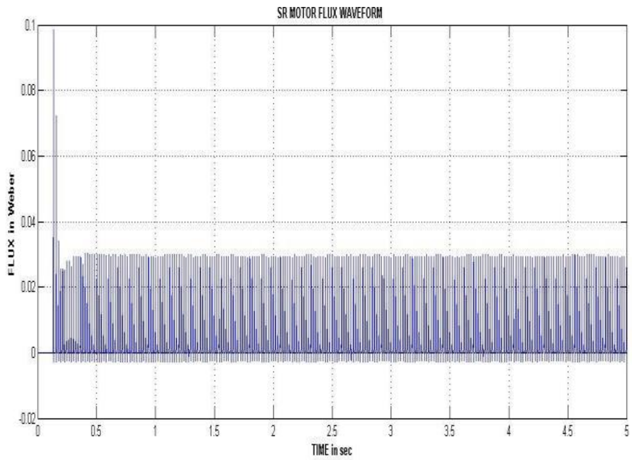
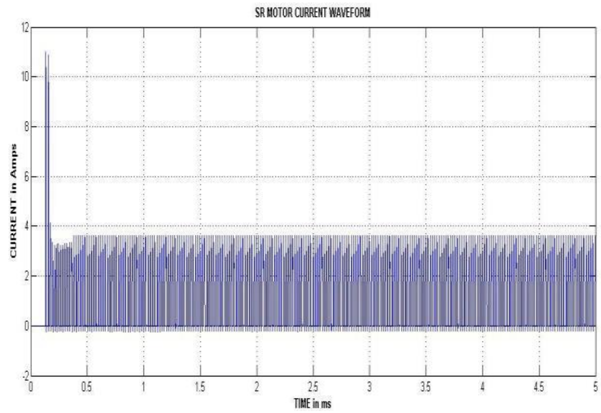


Fig - 9 Proposed system SR motor PWM pulses

3.3 FLUX, CURRENT & TORQUE WAVEFORM





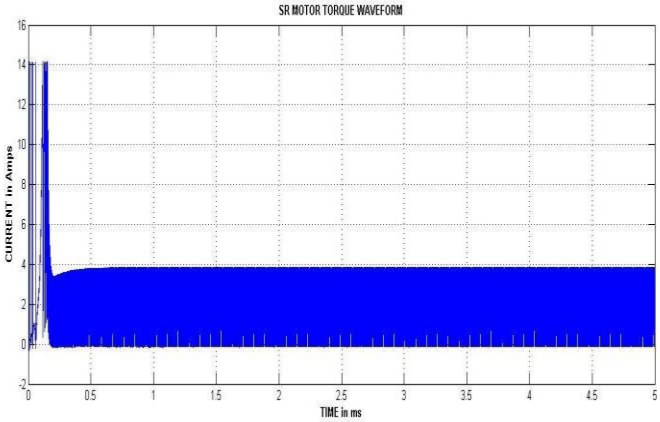


Fig – 10 Proposed system SR motor Flux Current & Torque Waveform

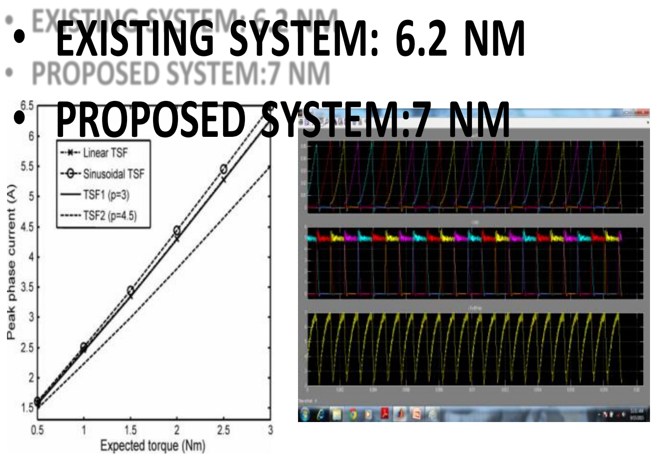


Fig - 11 Torque Improvement

3.4 SPEED WAVE FORM USING PI CONTROLLER

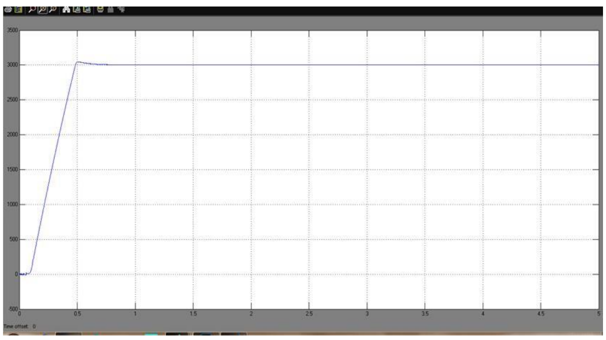


Fig - 12 Proposed system SR motor speed waveform using PI controller

4. CONCLUSIONS

In this project, the PI compensator using a linearized small-signal mode for SRM current loop is proposed. Based on the derived loop transfer function for the duty cycle to control output, the PI compensator can be designed. The results indicate that the PWM hysteresis current controller achieves numerous advantages:

1) Constant switching frequency, 2) low audible noise, 3) small current ripple, and 4) smooth torque production. A Hysteresis controller based SRM drive system was then implemented to verify the proposed technique.

Torque ripple and acoustic noise prevent SRM from high performanceapplication. Any work and research on torque ripple and acoustic noise minimization is useful and challenging. In addition, a speed loop can be implemented with digital signal process to keep constant speed under all the load conditions.

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