Design and Simulation of a Switched Reluctance Motor Using Sensorless Control System

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Abstract— This paper mainly introduces the acquisition of the position information of the switched reluctance motor through the inductance, which can make the switched reluctance motor (SRM) correct commutation. The main method is to apply high-frequency and low-duty pulse voltages to the two non-conducting phases of the switched reluctance motor when the motor is in low-speed operation, so that the non-conducting phase generates a response current through the rising slope of the response current The current change rate is obtained by the difference with the falling slope, and then the current change rate is converted into inductance through a formula, and whether the inductance reaches the inductance threshold is judged whether it reaches the commutation position, and the motor is subjected to timely and accurate commutation processing. This method is realized by MATLAB/Simulink simulation, and combined with the high-speed inductance method obtained by the flux ratio current, to realize the position sensorless technology combined with the inductance method in the full speed cycle, and the simulation verifies that the low-speed and high-speed algorithms can be smooth Switch, and can realize its commutation control function, and It provides simulation support for applications such as lawn mower.

Keywords— Switched reluctance motor, Inductance, Pulse injection, No position sensor etc.

I. INTRODUCTION

In order to ensure stable operation of a switched reluctance motor, it needs to obtain accurate commutation signals, which requires a position sensor to obtain the position of the rotor. Common position sensors include Hall sensors and encoder sensors. They all convert the real-time position signal of the motor into electrical signals and provide them to the control chip for commutation control. The position sensor ensures the smooth operation of the motor and provides a speed basis for the motor speed control system. But the position sensor still has many shortcomings.

First of all, although the switched reluctance motor can operate normally in harsh environments (high temperature, dust), the position sensor is more affected by the harsh environment and its accuracy is reduced, which limits the application of the switched reluctance motor in harsh environments. Nowadays, the main application areas of switched reluctance motors are still in the harsh environments with high dust and high temperature such as coal mines and aerospace [1]-[6].

Secondly, the position sensor increases the cost and volume of the entire control system, which forms a huge obstacle to the promotion and application of the switched reluctance motor, so the research on the position sensorless technology becomes particularly important. At present, many scholars have conducted research on the sensorless technology of switched reluctance motors, and have also proposed many feasible methods, which are gradually moving towards practicality.

Nowadays Switched Reluctance Motor (SRM) becomes more popular among the various electric drives available in the domestic and industrial application due to its simple and robust construction.

The application of the machine, the operation of SR Motor can be categorized in to the low and medium speed operation and high speed operation. The control of SRM drive is developed by the convertor circuit which control excitation of phase by SCS (switching convertor switches).

The developed SRM circuit suffers from low power factor and high harmonic capacity which affects the performance of SRM drive.

Rotor position of SRM is directly sensed by using sensor is called sensor type SRM. The torque ripples in the SRM are arising, due to phase current commutation.

The simulated performance of SRM drive system is presented to analyse the effect of switch angles on transient and steady state performance of the drive in terms of speed, current and torque response.

A new analytical representation and simulation of the phase inductance of SRM using MATLAB is presented. Simulation methods have following advantages.

- It is free from expression
- Can be applied widely
- Demonstrates inductance profile using motor parameters only
- Saves run time.

II. PROBLEM IDENTIFICATION

The switched reluctance motor represents one of the earliest electric machines which were introduced two centuries back in the history.

The problems associated with the induction and dc machine together with revolution of power electronics and semiconductors in the late sixties of the last century led to the reinvention of this motor and redirected the researchers to pay attention to its attractive features and advantages which helped in overcoming a lot of problems associated with other kinds of electrical machines such as brushes and commutators in dc machines and slip ring in wound rotor inductions machines besides the speed limitation in both these motors.

The simple design and robustness of the switched reluctance motor made it an attractive alternative for these kind of electrical machines for many applications recently specially that most of its disadvantages which are mentioned in this project.

III. PROPOSED SYSTEM

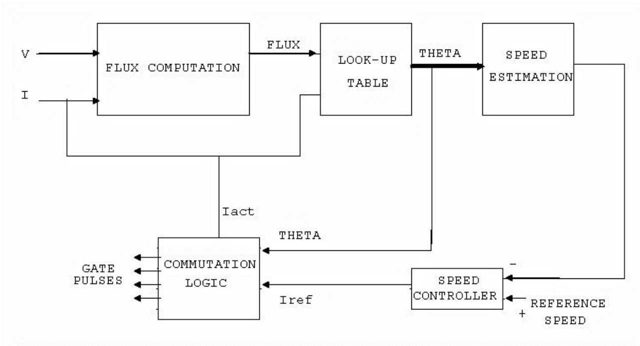


Fig. 1. Block Diagram of system

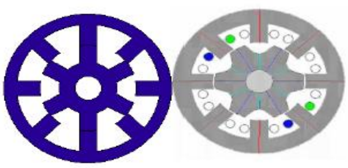
- SRM model is simulated in MATLAB/SIMULINK environment in Sensor-less mode. Flux-current method is used for simulating the model.
- The SRM flux-current characteristics are stored in the form of look-up table. Voltage and current are used for calculating flux; this calculated flux along with current is fed to ψ-*i*-θ look-up table, which gives rotor position θ as output.

This rotor position along with current is fed to look-up table, which gives torque as output. Rotor position information is obtained from this look up table ψ-*i*-θ, which is accordingly used for carrying out the commutation of different phases.

IV. SRM SPECIFICATION

SRM Drives

Switched reluctance motor (SRM) is a rotating electrical machine and falls under a special class of motor wherein both stator and rotor have salient poles. It is a type of a stepper motor, an electric motor that runs by reluctance torque.



(a) (b)

Fig.2. A typical 4 phase SRM with eight stator/ six rotor poles (a) Pole configuration (b) Switching Pattern

- Stator winding comprises of a set of coils, each of which is wound on one pole. SRM is excited by a sequence of current pulses applied at each phase. The individual phases are consequently excited, forcing the motor to rotate. The rotor does not have any windings or magnets. It is made up of silicon steel, so the inertia of the rotor is very less.
- The stator and the casing are connected to facilitate heat dissipation. The rotor has no complicated structure. The entire motor body is parallel.
- Without permanent magnets, SRM has the advantages of low cost, simple structure and long life compared with permanent magnet synchronous motors.
- The stator and rotor structures of common SRM motors include two-phase 4/2 poles, three-phase 6/4 poles.

SRM Configurations

- Switched reluctance motors come in different configurations such as 12/8, 8/6, 6/4, and 4/2. But here, our emphasis is on 6/4 configuration.
- This has 3-pole pairs at the stator and 2-pole pairs at the rotor. It is also referred to as 3-phase SRM.
- The SRM is fed by a threephase asymmetrical power converter having three legs, each of which consists of two IGBTs and two freewheeling diodes.
- During conduction periods, the active IGBTs apply positive source voltage to the stator windings to drive positive currents into the phase windings.
- During free-wheeling periods, negative voltage is applied to the windings and the stored energy is returned to the power DC source through the diodes.
- The fall time of the currents in motor windings can be thus reduced. By using a position sensor attached to the rotor, the turn-on and turn-off angles of the motor phases can be accurately imposed.
- These switching angles can be used to control the developed torque waveforms. The IGBTs switching frequency is mainly determined by the hysteresis band.

Construction Of SRM Circuit

- In switched reluctance motor the torque is developed because of the tendency of the magnetic circuit to attain the minimum reluctance i.e. the rotor moves line with then stator pole thus maximizing the inductance of the excited coil.
- When a rotor pole is aligned with a stator pole, there is no torque because field lines are orthogonal to the surfaces. If one displaces the rotor of its position, there will be torque production that will tend to bring back the rotor toward the aligned position. If current is injected in the phase when in the unaligned position there will not be torque production.
- If one displaces the rotor of the unaligned position, then a torque tends to displace the rotor towards the next aligned position. The magnetic behaviour of SRM is highly nonlinear.
- But by assuming an idealistic linear magnetic model, the behaviour pattern of the SRM can be easily studied without serious loss of integrity from the actual behaviour

pattern. SRM, when compared with the other AC and DC machines has some advantages and limitations.

- Changing the shape and size of stator and rotor
- Dimensional variations for stator and rotor poles

- Rotor poles for the 3-phase, 6/4 poles SRM. After gathering the results of the highest developed torque for the stator, and the rotor poles, a new SRM optimized design is obtained.

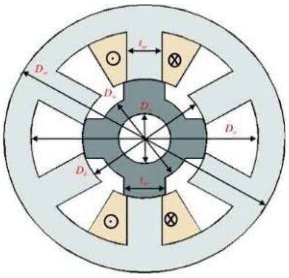


Fig.3. Shows Flux Density of 6/4 Pole SRM and Base Design of SRM

The base design and the optimized design for 3- phase, 6/4 poles SRM. The stator pole arc/pole pitch ratio (β) for the optimized SRM is 0.5; the rotor pole arc/pole pitch ratio Υ for optimized SRM is 0.38. Fig.3 shows the flux density through the stator pole, air gap, and rotor for 3- phase, 6/4 poles base and optimized cross section design SRM.

V. PERFORMANCE ANALYSIS

Efficiency Characteristics:

- Efficiency is a crucial parameter in motor performance analysis as it indicates how effectively electrical energy is converted into mechanical energy. The efficiency of an SRM depends on factors such as the design of the motor, operating conditions, and control strategies.
- Efficiency can be analyzed experimentally by measuring input power (electrical) and output power (mechanical) under different load and speed conditions. In MATLAB, you can simulate the motor behavior using mathematical models and perform efficiency calculations based on simulated data.
- Efficiency maps can be generated to visualize the motor's efficiency across its operating range. This helps identify optimal operating points and efficiency improvements through design optimization or control strategies.

Torque-Speed Characteristics:

- Torque-speed characteristics describe the relationship between torque output and rotational speed of the motor. Understanding these characteristics is essential for determining the motor's performance in various applications.
- Torque-speed curves can be generated experimentally by measuring torque and speed at different operating points. In MATLAB, you can simulate the motor behavior and plot torque-speed curves based on simulation results.
- Analysis of torque-speed characteristics helps assess the motor's ability to deliver sufficient torque at different speeds and identifies speed ranges where the motor operates efficiently.

Comparison with Other Types of Motors:

- Comparing SRMs with other types of motors such as induction motors and permanent magnet motors provides insights into their relative advantages and disadvantages.
- MATLAB simulations can be used to compare the performance of different motor types under various operating conditions. Key parameters for comparison include efficiency, torque-speed characteristics, power density, cost, and suitability for specific applications.
- Through performance analysis and comparison, you can identify scenarios where SRMs offer advantages over other motor types, such as high-speed applications, harsh environments, or variable load conditions.

Description (6/4 specific model):

- The SRM is fed by a three-phase asymmetrical power converter having three legs, each of which consists of two IGBTs and two free-wheeling diodes. During conduction periods, the active IGBTs apply positive source voltage to the stator windings to drive positive currents into the phase windings.
- During free-wheeling periods, negative voltage is applied to the windings and the stored energy is returned to the power DC source through the diodes. The fall time of the currents in motor windings can be thus reduced. By using a position sensor attached to the rotor, the turn-on and turn-off angles of the motor phases can be accurately imposed. These switching angle can be used to control the developed torque waveforms.
- The phase currents are independently controlled by three hysteresis controllers which generate the IGBTs drive signals by comparing the measured currents with the references. The IGBTs switching frequency is mainly determined by the hysteresis band.

Simulation (6/4 specific model):

- In this model, a DC supply voltage of 240 V is used.
- The converter turn-on and turn-off angles are kept constant at 45 deg and 75 deg, respectively, over the speed range. The reference current is 200 A and the hysteresis band is chosen as +-10 A.
- The SRM is started by applying the step reference to the regulator input. The acceleration rate depends on the load characteristics. To shorten the starting time, a very light load was chosen.
- Since only the currents are controlled, the motor speed will increase according to the mechanical dynamics of the system. The SRM drive waveforms (phase voltages, magnetic flux, windings currents, motor torque, motor speed) are displayed on the scope.
- As can be noted, the SRM torque has a very high torque ripple component which is due to the transitions of the currents from one phase to the following one. This torque

ripple is a particular characteristic of the SRM and it depends mainly on the converter s turn-on and turn-off angles.

- In observing the drive's waveforms, we can remark that the SRM operation speed range can be divided into two regions according to the converter operating mode: current-controlled and voltage-fed.

Current-controlled mode

- From stand still up to about 3000 rpm, the motor's emf is low and the current can be regulated to the reference value. In this operation mode, the average value of the developed torque is approximately proportional to the current reference.
- In addition to the torque ripple due to phase transitions, we note also the torque ripple created by the switching of the hysteresis regulator. This operation mode is also called constant torque operation.

Voltage-fed mode

- For speeds above 3000 rpm, the motor's emf is high and the phase currents cannot attain the reference value imposed by the current regulators. The converter operation changes naturally to voltage-fed mode in which there is no modulation of the power switches.
  - They remain closed during their active periods and the constant DC supply voltage is continuously applied to the phase windings. This results in linear varying flux waveforms as shown on the scope.

In voltage-fed mode, the SRM develops its 'natural' characteristic in which the average value of the developed torque is inversely proportional to the motor speed. Since the hysteresis regulator is inactive in this case, only torque ripple due to phase transitions is present in the torque waveforms.

Optimization of the Torque Characteristic - Adaptive Switching Angle

- In SRM drives, both the average torque and torque ripple are affected by the turn-on and turn-off angles and by the current waveforms in the motor phases. And these characteristics change as a function of the motor speed.
- In many applications, electric vehicle drives for instance, it is highly desirable to have highest torque/ampere ratio and lowest torque ripple and this over a widest speed range possible.
- The SRM torque characteristic can be optimized by applying appropriated pre-calculated turn-on and turn-off angles in function of the motor current and speed.
- The optimum values of optimum angles can be stored in a 2-D lookup table.

Efficiency Calculation:

- The efficiency (η) of an SRM can be calculated as the ratio of mechanical power output (P_{out}) to electrical power input (P_{in}):

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

- Where:
- (P_{out}) = Torque(T) x Angular Speed (ω)

P_{in} = Volage(V) x Current(I)

Torque-Speed Relationship:

- The torque (TT) produced by an SRM is given by:

$$T = \frac{1}{2} \times k_t \times \Phi \times I$$

Where:

- k_t= Torque Constant
- Φ = Flux Linkage
- I=Current

Flux Linkage Calculation:

- The flux linkage (Φ) in an SRM is influenced by the current (I) and rotor position (θ):

$$\Phi = \frac{N \times \lambda \times I}{2 \times \pi} \times f(\theta)$$

Where:

- N = Number of turns in the winding
- λ = Inductance

$f(\theta)$= Flux function

The basic model of the motor used in the simulink system, the motor parameters are 240V DC voltage power supply, 6/4 type motor, stator resistance 0.05 ohm, 48KW power, on-current set to 200A fluctuates 10A up and down. PID double closed loop current speed control, build low-speed algorithm to obtain inductance module, high-speed algorithm to obtain inductance module, commutation control module, etc. The simulation system of SRM without position sensor is shown in the figure below.

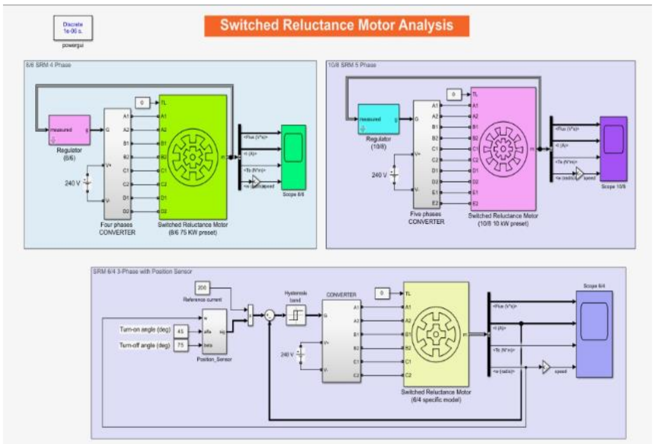


Fig.4.General block diagram of simulink sensorless system

- The low-speed algorithm module is,

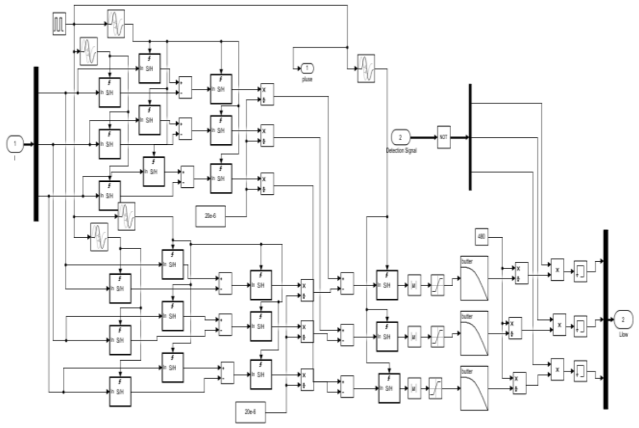


Fig.5. Low-speed algorithm module

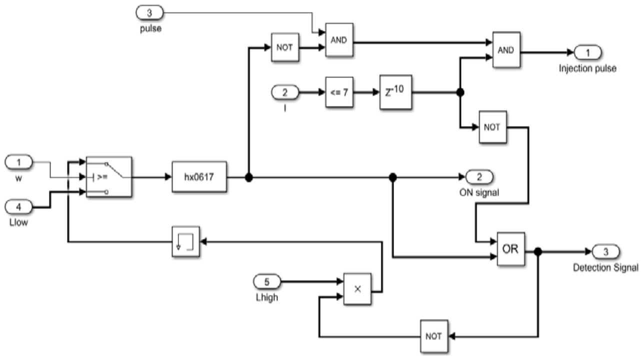


Fig.6. Commutation logic module

VI. RESULT ANALYSIS

When the commutation control module is set at 1200r/min, the motor switches from low-speed algorithm to high-speed algorithm, that is, the inductance is provided by the high-speed module, the commutation logic is programmed by S-function, and the commutation control signal is output to determine the three-phase motor's Each phase is on and off.

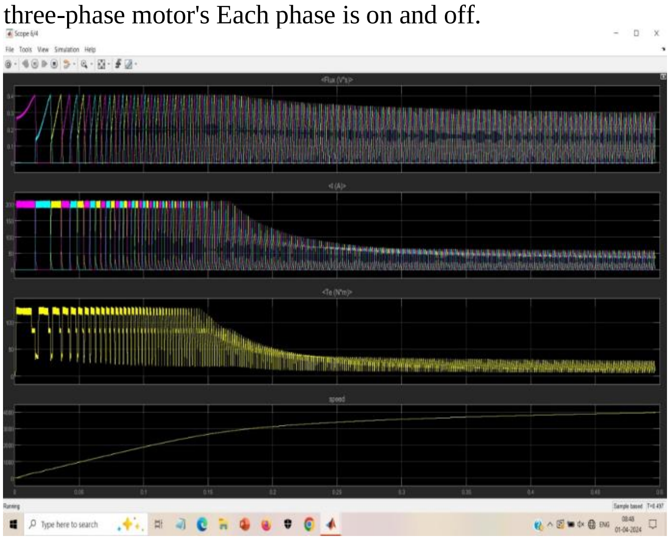


Fig. 4. Waveform diagram of flux linkage, current, torque and speed.

Under no-load conditions, it can be seen that the motor speed rises from 0r/min to 1200r/min and then smoothly accelerates to the closed-loop reference speed of 3000r/min, realizing the static, low-speed, and high-speed full-speed operation of the SRM, And the speed remains stable after reaching the reference speed, the flux linkage and current signals are symmetrical. The inductor is obtained by injecting current into the idle phase and integrating the voltage of the conducting phase in the low speed range. The work and simulation verification proves the feasibility of position sensorless control of SRM based on the inductance method, and provides theoretical and simulation support for the materialization and productization of position sensors, but the simulation is only in ideal conditions When running under the environment, physical research needs to consider signal interference, sampling accuracy, high-frequency noise and other factors that may affect the results. Productization still requires your continuous efforts.

VII. ADVANTAGES

- Switched Reluctance Motors (SRMs) offer several advantages in sensorless control systems:
- Simplicity: SRMs have a simple and robust construction with no windings on the rotor, making them mechanically robust and suitable for high-speed applications.
- High Efficiency: SRMs have a high efficiency over a wide range of speeds and loads, making them suitable for variable speed drive applications where energy efficiency is crucial.
- Sensorless Operation: SRMs can be operated without the need for position or speed sensors, reducing system complexity, cost, and maintenance requirements.
- Fault Tolerance: SRMs are inherently fault-tolerant due to their simple construction and can continue to operate even in the event of a stator or rotor winding fault.
- Adaptability: SRMs are suitable for harsh operating environments, including high temperatures and vibrations, making them suitable for a wide range of industrial applications.
- Regenerative Braking: SRMs can be easily configured for regenerative braking, allowing for energy recovery during deceleration, thereby improving overall system efficiency.
- Cost-Effectiveness: SRMs are often more cost-effective compared to other motor types, especially in high-speed and high-power applications, due to their simpler construction and lower manufacturing costs.

VIII. APPLICATION

- Electric Vehicles (EVs)
- Industrial Automation
- HVAC Systems (heating, ventilation, and air conditioning (HVAC) systems)
- Home Appliances
- Renewable Energy
- Pumps and Compressors
- Aerospace and Marine.

IX. CONCLUSION

This project has presented a simple method for designing SRM operating under sensor less condition. This SRM design method takes into account the practical machine constraints very easily and can be simply implemented as an enhancement to existing design methods.

The utilization of Switched Reluctance Motors in sensorless control systems offers numerous benefits across a wide range of applications. By eliminating the need for position or speed sensors, sensorless control systems simplify motor control, reduce system complexity, and lower overall costs.

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