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Simulation of Switched Reluctance Motor and Control Based on MATLAB Environment

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ABSTRACT

The first part of this master project report is the literature review of the switched reluctance motor (SRM) which includes the basic principle of the switched reluctance motor, motor topologies, mathematical approach, torque production, electromagnetic, drives, converters and its applications. This part means to help to understand the working principle and properties of SRM.

The second part of the report describes the work of modeling and simulating of SRM and its control drives. This model is based on the mathematical equations of SRM. All simulation results are shown in this part. The simulation results for different turn-off angle are discussed, and then the current control and speed control are applied. Some simulation results will be compared with the paper which is chosen from IEEE journal. The MATLAB code are set as m-file.

In the last part, some conclusion has been discussed.
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Chapter 1

1. Introduction

1.1 Overview

Switched reluctance motor (SRM) drives are simpler in construction compared to induction and synchronous motors. Their combination with power electronic controllers may yield an economical solution. The structure of the motor is simple with concentrated coils on the stator and neither windings nor brushes on the rotor. This apparent simplicity of its construction is deceptive. SRM drives present several advantages as high efficiency, maximum operating speed, good performance of the motor in terms of torque/inertia ratio together with four-quadrant operation, making it an attractive solution for variable speed applications. The very wide size, power and speed range together with the economic aspects of its construction, will give the SRM place in the drives family.

The performances of SRM strongly depend on the applied control. Three main parts can be identified: the motor itself, the power electronic converter and the controller. The drive system, comprising signal processing, power converter and motor must be designed as a whole for a specific application.

There is one converter unit per phase. A battery or a rectifier supplies the DC power. The basic principle is simple: each phase is supplied with DC voltage by its power electronic converter unit as dictated by the control unit, developing a torque, which tends to move the rotor poles in line with the energized stator poles in order to maximize the inductance of the excited coils. An important fact is that the torque production is independent of the direction of current, which contributes to the reduction of the number of switches per phase.

Figure 1. Switched reluctance motor drive system

Figure 1 shows the principal part of a SRM drive.
1.2 Objective

The purpose of this master project is to build a simulation model with MATLAB code for the SRM, to simulate its performance.

In order to fully understand the principle of SRM, literature review for SRM is necessary and very important.

The MATLAB code for SRM and its drive is set in M-file.

1.3 Report Structure

This report has been divided in 4 chapters.

- Chapter 1: a brief introduction of SRM;
- Chapter 2: literature review of SRM;
- Chapter 3: simulation results of SRM;
- Chapter 4: some conclusion.

All motor parameters and MATLAB code are shown in Appendix.
Chapter 2

2. Literature Review

SRM is an electric motor that converts the reluctance torque into mechanical power. In the SRM, both the stator and rotor have a structure of salient pole, which contributes to produce a high output torque. The torque is produced by the alignment tendency of poles.

2.1 Motor Topologies

As any other motor, the structure of SRM consists of a stator and a rotor. Both stator and rotor are laminated. Stacking the laminations punched from steel lamination with high magnetic quality yields the rotor cores. The stator is formed from punched laminations too bonded into a core, and the coils are placed on each of the stator poles.

Each stator pole carries an excitation coil, and opposite coils are connected to form one “phase”. There are no windings on the rotor.

Paper [1] presents a novel rotor structure optimized by using the level set method to improve the static torque characteristics of a high speed SRM.

It was reported that segmented rotor construction improves the torque output and efficiency. Paper [2] [3] discusses a SRM with segmented rotor construction designed for direct drive application. Such a motor has an outer rotor. It is found that in such motors, the torque output increases when there are higher number of rotor segments than stator poles.

SRM can offer a wide variety of aspect ratios and salient pole topologies without affecting performance too much. This means that each application is likely to be better suited for a specific switched reluctance topology.

The costs of SRM drives are a combination of the costs of the motor and the inverter. They strongly depend on the number of phases of the motor.

Paper [4] investigates the influence of physical size of SRM on its output performance, the comparison of magnetic characteristics and energy conversion loops of three SRMs that the output capability of SRMs will be reduced in different ways as the motor size is reduced.

2.1.1 Single Phase Motor

These are the simplest SRMs having the advantage of fewest connections between motor and power electronics. For the single phase motor, the quantity of the rotor poles are the same as the stator poles.

Figure 2 shows the geometries of single phase motor with 4 rotor poles and 4 stator poles.
Paper [6] shows the design of single SRM.

However, the very high torque ripple and inability to start at all angular positions represents a drawback. They can present interest only for very high speed applications.

In order to solve this problem, paper [7] shows a single phase SRM drive with saturation-based starting method.

Also, paper [8] presents a new single phase, hybrid SRM for low-cost, low-power, pump or fan drive systems. Its single phase configuration allows use of a simple converter to reduce the system cost. Cheap ferrite magnets are used and arranged in a special flux concentration manner to increase effectively the torque density and efficiency of this motor. The efficiency of this motor is comparable to the efficiency of a traditional permanent magnet motor in the similar power range.

Paper [9] presents a technique that uses rotor shorting rings to start the single phase SRM, from any rotor position, in a specified direction.

Paper [10] proposes the design process of the starting device which puts the rotor in the starting position before it is started and design the starting device composed of the parking permanent magnet for the prototype single phase SRM.


### 2.1.2 Two Phase Motor

The use of a stepping the air-gap can avoid the starting problems. For a two phase SRM the high torque ripple is an important drawback.

Figure 3 shows the geometries of 2 phase motor with 2 rotor poles and 4 stator poles.
Paper [12] presents a novel two phase SRM that is conceived for high efficiency operation and full load starting performance for any initial rotor position. The principle of operation of the proposed motor and its unique features such as the flux-reversal-free stator for reducing core losses, the utilization of only two thirds of the stator core for each phase operation.

A novel two phase SRM with a stator composed of E-core structure having minimum stator core iron is proposed in paper [13] [14]. The E-core stator has three poles with two poles at the ends having windings and a center pole containing no copper windings.

### 2.1.3 Three Phase Motor

The most popular topology of a three phase is the 6/4 form (stator poles = 6 and rotor poles = 4). It represents a good compromise between starting and torque ripple problems and number of phases. Alternative three phase motors with doubled-up pole numbers can offer a better solution for lower speed applications.

Figure 4 shows the geometries of 3 phase motor with 4 rotor poles and 6 stator poles.

Paper [15] shows a wound-field three phase flux switching synchronous motor with all excitation sources on the stator, the design adopted, though allowing room for improvement, produced torque which matched a conventional SRM of the same size at the same electric loading.
In paper [16], it identifies stator/rotor geometrical design variables that influence the cogging, interaction torques, and winding flux linkage using a two-dimensional finite-element method and the flux-magneto motive force diagram technique. Also, the novel design to improve the performance of the SRM is studied.

In paper [17] the systematic approach to the design of an asymmetrical three phase SRM with wide constant power range is described. It is shown that the SRM configuration with an unequal number of turns per phases may provide a wider constant power range than a corresponding symmetrical one.

Paper [18] presents a novel electromagnetic actuator having two degrees of freedom for rotational and linear actuation. Torque and thrust can be controlled independently.

### 2.1.4 Four Phase Motor

The four phase motor is known for reducing torque ripple. The large number of power electronic devices and connections is a major drawback, limiting four phase motors to a specific application field. A practical limitation to consider larger phase numbers is the increase of the converter phase units, hence of the total cost.

Figure 5 shows the geometries of 4 phase motor with 6 rotor poles and 8 stator poles.

![Image of 4 phase motor with 6 rotor poles and 8 stator poles](source: Fleadh) [5]

A comprehensive time-stepping finite-element behavioral model is developed and utilized for detailed analysis and design refinements of a prototype 8/4 SRM is presented in paper [19].

### 2.1.5 Five and More Phase Motor

Generally, increasing the number of SRM phases reduces the torque ripple, but at the expense of requiring more electronics with which to operate the SRM. At least two phases are required to guarantee starting, and at least three phases are required to insure the starting direction. The number of rotor poles and stator poles must also differ to assure starting.

Figure 6 shows the geometries of 5 phase motor with 8 rotor poles and 10 stator poles.
2.1.6 Other Novel Motor

Paper [20] [21] [22] [23] show several novel SRMs configuration with higher number of rotor poles than stator poles. The simulation results show that this motor produces higher torque per unit volume and comparable torque ripple when compared to a conventional SRM.

Paper [24] shows a new double-layer-per-phase isolated SRM, this configuration for SRM which can be proposed as a suitable candidate for high torque and low flux leakage SRM. Unlike the conventional SRM, this configuration has no direct windings wrapped on the stator poles. This motor consists of three different sets, and each set has one concentric independent winding, two layers of the stator poles, and three layers of the rotor poles in which the middle rotor layer acts as a core for phase winding.

Also paper [25] proposed novel SRM consists of three magnetically independent modules, where each module is known as a phase or a layer.

SRM has a good feature as a bearing-less motor owing to the inherent magnetic attraction force in the radial direction between the rotor and the stator pole. This radial force can suspend the rotor, and the mechanical bearing that is placed in the front and the end of the motor can be replaced with a suitable inherent radial force. The bearing-less structure is very useful for mechanical maintenance and friction of bearing, temperature intensity and environmental fault tolerance. As the bearing ability and the motor are integrated into a compact unit and the bearing-less motor is essentially maintenance-free, they are particularly suitable for operating in special environments such as blood pumps.

Paper [26] [27] are designs of novel bearing-less SRMs. Different from the conventional bearing-less SRMs, the suspending poles of the proposed bearing-less SRMs are separated from the phase torque poles. Perpendicularly placed suspending poles are designed to produce a continuous radial force for rotor bearing. Owing to independently placed suspending and torque poles, the produced suspending force has excellent linearity according to rotor position and independent characteristics of the torque current. The control of air gap is easier than the conventional one from the linear and independent characteristics.

In paper [28], an optimum design criteria for maximum torque density and minimum torque ripple of a SRM using response surface methodology and finite-element method. The focus of this paper is to find a design solution through the comparison of torque density and torque ripple according to rotor shape variations. Then, a new type winding method and optimum turns of armature/field
winding are introduced, and numerical analysis and experiment are conducted to confirm the appropriate solution for the optimized model.

Paper [29] presents a novel SRM that has auxiliary windings and permanent magnets on the stator yoke. It can be driven by an asymmetric half bridge converter in the same manner as the conventional SRM, and the performance is improved by the auxiliary windings and magnets. This motor has easily obtainable ferrite magnets and auxiliary windings to improve the power and efficiency since they can raise the utilization factor of the iron core.

Paper [30] describes the design of an axial-type SRM with the aim of improving the output torque characteristic. The axial-type structure has several advantages, including a large air-gap area due to the dependence on the radial length, whereas the air-gap area of the radial-type motor depends on the axial length. This advantage is expected to increase the inductance and the output torque.

Paper [31] [32] [33] present the mutually coupled dual-channel SRMs to produce higher torque density and decrease the noise emission and torque ripple.

Paper [34] is the comparison studies between classical and mutually coupled SRMs using thermal-electromagnetic analysis for driving cycles.

It shows that for the conventional SRM the majority of the force of produced is in the radial direction and does not contribute to motion. If the normal forces happen to be in the direction of motion, a larger motional force profile for SRM is yield. Based on these guidelines, a new SRM is proposed in paper [35].

In paper [36], a novel type of hybrid reluctance motor drive is presented. This new motor is characterized by a stator formed by a combination of independent magnetic structures, each one composed of an electromagnet, the magnetic core with one or several coils wound on it, associated with a permanent magnet disposed between their poles. The rotor has the same configuration of a SRM without any coil, magnets, or squirrel cage. This new type of motor does not present cogging torque and has higher power and efficiency than a SRM of the same size.

Paper [37] presents a novel SRM with wound-cores placed on stator and rotor poles. The wound-core is made of grain-oriented silicon steel, which exhibits high saturation magnetic flux density and less core loss.

Paper [38] presents a novel SRM design in which the stator is simply formed from C-cores. The comparison shows that the proposed SRM performs well in terms of torque and efficiency, and provides a higher degree of flexibility in winding design.

In paper [39], a novel design to improve the performance of a SRM is proposed. The proposed SRM has permanent magnets parallel to the stator magnet flux lines and thus is much more difficult to demagnetize, it is shown that the proposed SRM has an improved performance.

### 2.2 Basic Switched Reluctance Motor Principles

The basic operating principle of the SRM is quite simple: as current is passed through one of the stator windings, torque is generated by the tendency of the rotor to align with the excited stator pole. The direction of torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flow through the phase winding.
Continuous torque can be produced by intelligently synchronizing each phase’s excitation with the rotor position.

Figure 7 illustrates the cross-section of a three phase 6/4 SRM, in which the coils of the pole winding are connected in series and $i$ is the current of a single phase.

SRM with its passive rotor has a simple construction. However, the solution of its mathematical model is relatively difficult due to its dominant non-linear behaviour. The SRM is characterized by its geometrical layout, the characteristic of the magnetic material and electrical parameters. Paper [41] analysis the geometrical parameters on a double-sided linear SRM, such as pole width, pole length etc.

A torque is produced when one phase is energized and the magnetic circuit tends to adopt a configuration of minimum reluctance, i.e. the rotor poles aligned with the excited stator poles in order to maximize the phase inductance. As the motor is symmetric, it means that the one phase inductance cycle is comprised between the aligned and unaligned positions or vice versa as shown in Figure 8.
2.2.1 The Aligned Position ($L_a$)

Consider a pair of rotor and the stator poles to be aligned. Applying a current to phase establishes a flux through stator and rotor poles. If the current continues to flow through this phase, the rotor remains in this position, the rotor pole being “stuck” face to face to the stator pole. This position is called aligned position, and the phase inductance is at its maximum value ($L_{max}$ or $L_a$) as the magnetic reluctance of the flux path is at its minimum.

2.2.2 Intermediate Rotor Positions ($L_{int}$)

At intermediate positions the rotor pole is between two stator poles. In this case the induction is intermediate between the aligned and unaligned values. If there is any overlap at all, the flux is entirely diverted to the closer rotor pole and the leakage flux path starts to increase at the base of the stator pole on one side.

2.2.3 The Unaligned Position ($L_u$)

In the unaligned position, the magnetic reluctance of the flux path is at its highest value as a result of the large air gap between stator and rotor. The inductance is at its minimum ($L_{min}$ or $L_u$). There is no torque production in this position when the current is flowing in one the adjacent phases. However, the unaligned position is one of unstable equilibrium.

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 ($\beta_r - \beta_s$), attaining the minimum reluctance position and at this position phase inductance is maximum ($L_a$). 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 ($\beta_s + \beta_r$), the position is said to be the unaligned position and at this position the phase has minimum inductance ($L_u$). Although the concept of inductance is not valid for a highly saturated motor like SRM, the unsaturated aligned and unaligned incremental inductances are the two key reference positions for the controller. The relationship between inductance and torque production according to rotor position is shown in Figure 8.

Paper [43] proposes a simple equivalent circuit and mathematical model for the magnetic system of SRM based only on aligned and unaligned position data.

2.2.4 Torque-speed Characteristics

The torque-speed characteristics of a SRM is shown in Figure 9. Based on different speed ranges, the motor torque generation has been divided into three different regions: constant torque, constant power and falling power region.

The basic speed $\omega_b$ is the maximum speed at which maximum current and rated torque can be achieved at rated voltage. Below $\omega_b$, the torque can be maintained constant or control the fat-top phase current. At low speed, the phase current rises almost instantly after the phase switches turn-on since the back EMF is small at this time. So it can be set any desired level by mean of regulators (hysteresis or PWM controller). Therefore, the adjustment of fire angle and phase current can reduce noise and improve torque ripple or efficiency.

With speed increase, the back EMF is increased. An advance turn-on angle is necessary to reach the desired current level before rotor and stator poles starts to overlap. The desired current level
depends on the speed and the load condition. At the same time, since no current chopping appears during the dwell angle, only the angle control can be used at this stage. So the torque cannot be kept constant and is falling linearly with the speed increase, resulting in a constant power production.

In the falling power region, as the speed increases, the turn-on angle cannot be advanced further. Because torque falls off more rapidly, the constant power cannot be maintained. As the speed grows, the tail current of the phase winding extends to the negative torque region.

The tail current may not even drop to zero. In the high speed operation, the continued conduction of current in the phase winding can increase magnitude of phase current and the power density can be increased.

The influence of the rotor pole-arc and asymmetry of the pole surface on the torque-rotor position characteristic of a one phase SRM has been investigated by both 2-D and 3-D finite-element analysis and validated experimentally in paper [44].

### 2.3 Torque Production

The torque or force production in a SRM may be found from the variation of the stored magnetic energy as a function of the rotor position. This relationship is also used to analyse electromagnetic relays, holding magnets, solenoid actuators, and other devices where force is produced between two magnetic surfaces, including all motors with saliency.

The details of mathematical equations and torque production please see chapter 3 in this report and the paper [45] [46].

Also, a detailed mathematical model to a research of electromechanical processes in electric drives with SRM with buffers of an energy is explained in paper [47].
Paper [48] proposes a method for fast calculation of radial force and torque of a bearing-less SRM operating in a region of magnetic saturation.

In paper [49], stochastic response surface methodology and moving least square method are combined together in order to much more precisely predict the torque characteristics.

In paper [50] [51], the results of a 2-D finite-element analysis carried out on an 8/6 SRM for studying the effects of non-uniform air-gap on the torque profiles are presented.

In paper [52], the torque profiles of a finite-element analysis carried out on an 8/6 SRM having special pole face shapes are presented.

A new torque estimator for SRM drives based on 2-D rotary regression analysis is presented in paper [53].

**2.4 Flux Linkage**

Flux linkage characteristics are crucial for modelling, simulation and model-based control of SRMs. A method to obtain flux linkage characteristics of the SRM is presented in paper [54]. The proposed method avoids the usage of a clamping device or a search coil so that it is sometimes more applicable for practical implementations. The proposed method calculates flux linkage with the measured rotor position, phase voltage and phase current of the SRM running in steady states.

In paper [55], a fast measurement method of the flux linkage profile is proposed. In the proposed method, the rotor is first rotated to the aligned position, and then, the voltage pulses are applied to all phases simultaneously. The DC voltage and phase current waveforms are recorded to estimate the flux linkage curves at three different positions. These curves are used to calculate the coefficients of a second-order Fourier series flux linkage model, which represents the entire flux linkage profile of a SRM.

A novel BVC-RBF neural network based system simulation model for SRM has been developed in paper [56]. For accurately calculating the flux linkage characteristics, a double scalar magnetic potential method based 3-D finite-element method and a new enhanced incremental energy method are utilized.

Paper [57] presents a novel strategy of SRM optimal design. The strategy is based on the so called flux linkage characteristic. In this paper, first the desired flux linkage characteristic is identified, and then the optimal design parameters are sought after starting form this “idealized characteristic”.

Paper [58] proposes an accurate method to model the SRM magnetization characteristic, representing the accurate inductance profile, in order to achieve higher control performance. The proposed method makes use of a DC voltage in one phase of the SRM, with its rotor blocked in a fixed position.

Paper [59] presents a novel numerical method to calculate the magnetic characteristics for SRM drives. In this method, the 2-D orthogonal polynomials are used to model the magnetic characteristics. The proposed method is very helpful in torque prediction, simulation studies and development of sensor-less control of SRM drives.

Paper [60] proposes a simple method for measuring the parameters of SRM.
A simplified and fast built flux linkage analytical model for the SRM is proposed in paper [61], which utilises the Fourier series in expression of the current dependent arctangent function. The proposed model is shown to have a good degree of the accuracy.

Paper [62] presents the results of an investigation of components of the electromagnetic force in the air-gap of an 8/6 SRM. Using a Maxwell stress method, variations of radial and tangential force components due to saliency of the motor and saturation have been studied. This is a significant improvement, particularly for automotive applications where the difference in the required number of power electronics components can be justified.

The torque developed by a SRM is dependent on the change of flux linkage and rotor position. In paper [63], a simple analytical method (Flux Tube Method) to estimate the flux linkage characteristics of SRM is presented.

Paper [64] presents a spice-based flux linkage model for the SRM. In the proposed method, the flux linkage is represented by a limited number of Fourier series terms. This proposed model demonstrates a good representation of the characteristic in each phase, even if the motor is driven in the saturation region for steady-state operations.

Paper [65] has described the electromagnetic characterization of an 8/6 SRM from its initial 2-D finite-element method analysis using ANSYS.

Paper [66] presents a method to measure the flux linkage curves of a SRM that avoids the inherent errors introduced by iron and copper losses using the classic method of applying a voltage to the phase of the SRM and integrating it, minus a resistive voltage drop to get the flux. In the proposed method, the flux is computed from the measured static torque using conservation of energy and from the SRM’s measured unaligned inductance.

Based on 2-D trigonometry, a new numerical method is presented in paper [67] to compute the nonlinear magnetic and electromagnetic torque characteristics in SRM. In the proposed method, the mathematical model is composed of the 2-D truncated Fourier series. The results demonstrate that the proposed method can be used to precisely compute the nonlinear magnetic and torque characteristics in SRM.

Paper [68] describes an accurate and fully automated digital method (based on DSP) for the measurement of the magnetic characteristic of SRM, which includes online offset-error removal and winding resistance estimation.

Paper [69] presents a comprehensive discussion and analysis on the different computer-based methods for the determination of these characteristics for a typical. A DSP-based completely automated SRM drive system has been used for these studies.

In paper [70], a simple pure flux linkage measurement method is discussed and evaluated, which does not require a search coil.

Paper [71] proposes a rapid analytical solution for determining the aligned and unaligned flux linkage using a magnetic circuit model. It presents a simple method for obtaining the air-gap performance for unaligned linkage. The results of this method agree well with FEA solutions.

Paper [72] presents a real-time model to identify the inductance and the flux linkage of SRM. A dynamic measurement method is used for the real-time modeling. An artificial neural network,
designed in accordance with the inductance and the flux linkage data obtained from the dynamic measurement method, is used to make the real-time model.

Paper [73] performs analysis and experimental measurement of the electromagnetic force loads on the hybrid rotor in a novel hybrid magnetic-bearing SRM.

2.5 Motor Loss

Paper [74] provides a core loss model, the core loss estimation of SRM is complicated because it is not easy to predict the flux waveforms within the motor accurately and the flux waveforms are completely non-sinusoidal as well.

The iron loss model in paper [75] separates the iron losses into two components, eddy-current and hysteresis losses, and models the losses as a function of the derivative of flux density. The model is suitable for the non-sinusoidal flux densities in the SRM and predicts the iron losses as a function of time. The model is general and can be applied to any electromagnetic device with known geometry and material property.

Paper [76] illustrates that iron loss can affect the performance of a SRM and details a method for measuring the iron loss.

Paper [77] presents the loss trend inside a SRM, showing the core loss variation of the motor and it identifies the flux density harmonics that contribute to higher core losses in the rotor.

Paper [78] describes modelling of iron loss and its effect on current waveform in a rudimentary one-phase static SRM, and the development of a dynamic model, including instantaneous torque, of a three phase motor with eddy-current, hysteresis and additional iron losses.

Paper [79] investigates the losses that may occur in the windings of a SRM due to additional eddy currents. Essentially, turns on the surface of the leading-edge coil side of the stator pole will experience a magnetic field during the conducting cycle in a similar manner to an air-gap winding.

Paper [80] presents a reluctance network analysis model of a SRM considering iron loss. The proposed model consists of a multiple number of nonlinear reluctances and magnetic inductances that express magnetic hysteresis. The validity of the proposed model is proved by comparing calculated values with measured ones.

Paper [81] presents a new approach to reduce winding loss of SRM by changing the rotor shape. To predict the performance of improved SRM rotor, the parametric finite element analyses are needed to get inductance profiles of the proposed rotor shape.

Paper [82] presents a finite-element analysis of the temperature rise of SRMs due to electromagnetic losses. It estimates the various components of electromagnetic losses, including core loss in the lamination as well as copper and eddy-current losses in windings, and then predict the temperature rise within the motor due to these losses.

2.6 Electromagnetic Effect

Magnetic materials in electrical motors or actuators are submitted to multi-axial mechanical loadings. These stress states can be inherited from forming and assembly processes (cutting, stacking, welding, etc.) or appear in use (magnetic forces, inertial forces, etc.). On the other hand,
stress significantly modifies the magnetic behavior. The increase of manufacturing constraints (for cost reduction) and operating constraints (for cost reduction or compact purpose) emphasizes the need for appropriate coupled modeling tools in the design of electromagnetic systems.

Paper [83] proposes to implement a multi-scale model for magneto-elastic behavior into a finite-element code and provides a finite-element tool for the modeling of the effect of multi-axial stress on electro-technical devices.

The mutual saturation effect is analyzed in detail in paper [84]. The experimental results show the influence of the magnitude and direction of the leading phase current on the flux linkage of the working phase, and the influence of the trailing phase current on the flux linkage of the working phase.

2.7 Material

SRM has a doubly salient pole structure, and consists of only laminated core and windings. The concentrated windings are coiled around each stator pole, while the rotor is only made of laminated core. Hence, its performance greatly depends on magnetic properties of core material.

Paper [85] analysis the influence of various non-oriented electrical steels on motor efficiency and iron loss in SRM.

Paper [86] compares the SRM made of non-oriented silicon steel and permendur, and investigates the performance of a SRM made of permendur which has extremely high saturation flux density and very low core loss.

Dynamic hysteretic effects of magnetic materials are usually neglected in actuators modeling. In order to take into account these effects, paper [87] coupled a 2-D finite-element model in an original way with a magnetic equivalent circuit by using dynamic hysteretic flux tubes. As an example of an application, it presents the model of an ultrafast SRM, in which the control of the power converter is of major importance, and where iron losses can reach critical values.

Paper [88] developed a method, based on the space mapping technique that optimizes the geometrical parameters of the SRM. It quantified the influence of the material degradation on the optimization of the SRM. The proposed method can lead to a more efficient design or production process of the SRM.

In paper [89], a comparison of the efficiency improvements that can be obtained in a SRM using different materials (low-loss magnetic steels) and addressing the winding slot fill is shown.

2.8 Switched Reluctance Motor Drives

As mentioned before, the basic operating principle of the SRM is quite simple: as current is passed through one of the stator windings, torque is generated by the tendency of the rotor to align with the excited stator pole. The direction of the torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flowing through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase’s excitation with the rotor position. The amount of current flowing through the SRM winding is controlled by switching on and off power electronic devices, such as MOSFETs or IGBTs, which can connect each SRM phase to the DC bus. The power electronic inverter topology is an important issue in SRM control because it largely dictates how the motor can be controlled.
Paper [90] shows the research progress of SRM drive system.

In paper [91], a low-cost and simply structured but high performance analog encoder with a proper control method suitable for the practical and stable SRM drive is proposed. The proposed encoder uses a simple structure with an optical and an analog gradation for high resolution of rotor position.

**2.8.1 Angle Control**

SRM drive is known to provide good adjustable speed characteristics with high efficiency. However, higher torque ripple and lack of the precise speed control are drawbacks of this motor. These problems lie in the fact that SRM drive is not operated with an mmf current specified for dwell angle and input voltage. To have precise speed control with a high efficiency drive, SRM drive has to control the dwell angle and input voltage instantaneously. The advance angle in the dwell angle control is adjusted to have high efficiency drive through efficiency test.

**2.8.2 Rotor Position**

In SRM drive, it is important to synchronize the stator phase excitation with the rotor position; therefore, the information about rotor position is an essential for the proper switching operation.

The position sensor can be an expensive part of a drive system, and because it will normally be subject to a hot and electrically noisy environment, it can also be unreliable. Clearly using a “sensor-less” method of control is appealing: Manufacturing complexity is reduced, there is the possibility of improved reliability and costs can be reduced. Sensor-less control is desirable, but most sensor-less methods involve extensive computation, which is prohibitively expensive at such high speeds.

Initial position estimation is an essential concern for SRM sensor-less controls. In paper [92], a method to estimate the initial rotor position of SRMs using bootstrap circuits is presented. This method seeks to obtain the rotor position at standstill by analyzing the time required for the charging current reaching its peak value in the bootstrap circuit.

Paper [93] proposes a method to obtain the rotor position of SRMs by means of voltage measurements. In this position-estimation method, an initial voltage distribution is imposed over the impedances of the resonant circuit after which the circuit is let to oscillate freely. During this phase of free oscillation, the induced voltage over a phase winding exhibits a damped oscillatory behavior, from which position information can be retrieved.

Paper [94] presents a novel methodology for position sensor elimination for SRMs. Using the voltage from each conducting phase and the reference current signal as inputs, the rotor speed is first obtained as the output of a neuro-fuzzy learning system used as a “virtual” speed sensor. Then, the rotor position is determined by integrating the estimated value of speed. The method in paper [95] improved neural network based on it.

Paper [96] presents another position estimation method using the first switching harmonics through Fourier series.

Paper [97] presents a method of accurate indirect position estimation for SRM s suitable for starting and continuous operation using pulse injection and two thresholds.

Paper [98] shows a sensor-less operation of an ultra-high-speed SRM.
Also, in SRMs, rotor position information can be extracted from the measurement of position-dependent phase voltage resonances, paper [99] analysis this method.

Paper [100] proposes an adaptive sensor-less position control system for a synchronous reluctance motor using dual current-slope estimating technique.

A new method called linear quadratic regression position estimation method for sensor-less starting of SRM has been developed in paper [101]. It is based on a polynomial model of the magnetic characteristics of the motor. The main feature is that no specific magnetic information is needed and no calculation of flux linkage or current gradients is necessary. Only current measurement is needed and hence the method is robust and can be easily adapted to any SRM. The calculations are also straightforward that only involve simple matrix and algebraic operations.

An advanced proportional-integral and proportional-differential controllers for speed and position controls, respectively, are adopted in paper [102]. A gain-scheduling technique is adopted in the speed controller design for providing high dynamic performance and precise position control. In order to improve the set-point tracking, a low-pass filter is included in the position controller. The proposed four-quadrant control scheme is based on the average torque control method. The turn-on and turn-off angles are online determined through simple formulas so as to reduce the torque ripple at an acceptable level over a wide speed range.

A novel analytical approach to model SRM is proposed in paper [103]. This method is based on decomposition of magnetic characteristics such as flux linkage to two vector functions of rotor position and stator current. It has been shown that this model is very appropriate for online identification and also implementation of model-based sensor-less position control techniques.

A position detection and drive system of a toroidal SRM using search coils is presented in paper [104]. Rotor position detection is achieved using the voltage waveform induced by the time-varying flux linkage in the search coils, and then the appropriate phases are excited to drive a SRM.

Paper [105] describes a novel angle estimation scheme for a real time DSP based SRM drive using fuzzy logic where several unique techniques are implemented to improve the estimation accuracy.

A method for the sensor-less start-up from standstill and rotating shaft conditions has been introduced in paper [106]. This method eliminates the problem of starting hesitation. Besides, it also offers adequate accuracy and requires no additional hardware or memory. In addition, the proposed method is relatively easy to implement and can be easily modified to fit SRMs with different pole configurations.

In paper [107], novel virtual position and current sensors are designed based on modelling of magnetic double saliency characteristics in SRM drives.

Paper [108] presents real-time verification of an artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS) based rotor position estimation techniques for a 6/4 pole SRM drive system. The techniques estimate rotor position by measuring the three phase voltages and currents and using magnetic characteristics of the SRM, with the aid of an ANN and ANFIS, in real-time environments.

Paper [109] establishes the asymmetry of mutual flux for even number of phase motor, gives the upper boundary of such asymmetry, and suggests to choose an odd number of phase SRM for high-
performance applications. Also, this paper demonstrates that position estimation accuracy in SRM can be improved considering the mutual coupling effect.

Paper [110] presents a novel numerical method, which will be referred as the position stepping method, to predict the performances of SRM drives.

In paper [111], a sensor-less rotor-position-measurement method for a SRM drive is presented. The method is based on estimating a particular rotor position on a phase-by-phase basis and measuring the flux linkage and current when the estimated position is reached.

In paper [112] an enhanced representation of the SRM is introduced, by defining an appropriate finite element model of the motor. This model enables accurate estimation of rotor position and electromagnetic torque, for any current configuration.

Paper [113] presents a sensor-less position estimation technique for SRMs operating in dynamic modes over a wide speed range including zero speed.

Paper [114] presents an improved impressed diagnostic pulse-voltage method to estimate the rotor position of a SRM with an external rotor.

In paper [115], through simulation and analysis, it is demonstrated that a minimal NN configuration is attainable to implement rotor position estimation in SRM drives.

### Turn-on and Turn-off Angle

SRM can be used either in starter operation or alternator operation according to different turn-on and turn-off angle settings. A large number of methods for optimising turn-on angle and turn-off angle have been presented during past years.

Paper [116] considers the problem of choosing the firing angles within two average torque control schemes for SRM, based on ‘current control’ and ‘voltage control’, respectively. And this paper develops a general theory of the optimal turn-off angle.

In paper [117], a new analytical method is proposed to produce optimal turn-on and turn-off angles, based on a non-linear inductance model of low-inductance region for SRM.

An efficient, easily implemented control algorithm for excitation angles is developed in paper [118]. The new approach provides for automatic turn-on angle adjustment without the need for motor parameters or self-tuning techniques.

### Four-quadrant Operation

Variable speed applications require usually a four-quadrant operation. The SRM allows this kind of control. The advantage of the SRM is that forward and reverse motoring/braking operations do not depend on the direction of the current flowing in the phase windings, but only on the rotor position.

The relationship between the output torque and motor speed at four quadrants is shown in Figure 10.
Paper [119] presents a two phase SRM drive with a single controllable switch is presented for four-quadrant operation and control.

A four-quadrant strategy under sensor-less control has been designed and implemented in paper [120]. It shows that four-quadrant sensor-less control of the SRM drive is a feasible technique and can be considered as a technology ready for application. This technique is especially helpful where the characteristics of the application calls for operating in two/four-quadrants.

Paper [121] presents the development of a four-quadrant SRM drive for high dynamic applications.

Paper [122] unifies the optimal control of a SRM in a four-quadrant drive with smooth transition between the control-mode operations.

Paper [123] presents the modeling, simulation, and control aspects of four-quadrant SRM drives.

### 2.8.5 Dynamic Operation

#### 2.8.5.1 PWM Control

The selection of the pulse width modulation strategy is an important issue in SRM control, as it dictates how the motor can be controlled. The PWM strategy is also directly related to the power electronic converter topology.

Figure 11 shows the block diagram of PWM Current Control. The actual speed is compared with reference speed and error is given to a PI controller which outputs current reference. The inputs to the PWM control are reference current, actual current, turn-on angle ($\theta_{on}$) and turn-off angle ($\theta_{off}$). The output of the controller gives signals to the asymmetrical converter.
In paper [124], it reviewed various current controllers reported in the literature and discussed their merits and demerits. And, it proposed and implemented a novel high-performance current controller based on iterative learning, which shows improved current tracking without the need for an accurate model.

A novel PWM switching method and control algorithm for SRM drive systems is proposed in paper [125].

### 2.8.5.2 Speed Controller

Fuzzy logic and proportional-integral (PI) controller are presented here. Tuning of PI gains can be realized using various methods. It is not intended in this thesis to advocate one or another speed controller type as best solution for SRM.

1. **Fuzzy logic**

Fuzzy logic applications in power electronics and drives are relatively new. The advantages of fuzzy logic controllers are:

- There is no need of exact knowledge of the mathematical model of the controlled process;
- More efficient control of non-linear systems due to the non-linear nature of the controller;
- Fuzzy controllers are relatively easy to implement;
- Lower cost than other intelligent control systems.

However, the main problem of a fuzzy controller is its stability.

A basic fuzzy control philosophy system structure, which consists of the knowledge base, the inference mechanism, the fuzzification interface, and the defuzzification interface, is shown in Figure 12. Essentially, the fuzzy controller can be viewed as an artificial decision maker that operates in a closed-loop system in real time. It grabs plant output $y(t)$, compares it to the desired input $r(t)$, and then decides what the plant input (or controller output) $u(t)$ should be to assure the requested performance. The inputs and outputs are “crisp”. The fuzzification block converts the crisp inputs to fuzzy sets, and the defuzzification block returns these fuzzy conclusions back into the crisp outputs.
Based on the redevelopment of control rule base, two modified PI-like fuzzy logic controllers with output scaling factor self-tuning mechanism are proposed and verified in paper [126] for application in the SRM drive system. The motivation of this paper is to simplify the program complexity of the controller by reducing the number of fuzzy sets of the membership functions without losing the system performance and stability via the adjustable controller gain.

Paper [127] presents a novel adaptive Takagi-Sugeno-Kang-fuzzy controller to regulate the speed of a SRM. The proposed controller comprises two parts: a TSK-fuzzy controller and a compensated controller. The TSK-fuzzy controller is the main controller, which is used to approximate an ideal control law. The compensated controller is designed to compensate the approximation error between the TSK-fuzzy controller and the ideal control law.

Paper [128] presents a novel adaptive fuzzy cerebellar model articulation controller (CMAC) to regulate the speed of a SRM. The proposed controller comprises two parts—a fuzzy cerebellar model articulation controller and a compensating controller. The fuzzy CMAC learns and approximates system dynamics; the compensating controller compensates the approximation error of the fuzzy CMAC.


A novel fuzzy-neural system, which is referred to as a radial basis function network-based adaptive fuzzy system, is presented in paper [130], to model the SRM and predict the dynamic performances in a SRM drive system.

An adaptive fuzzy controller has been designed in paper [131] to develop a high-performance fault-tolerant SRM drive.

(2) Proportional-integral (PI) controllers

Proportional-integral (PI) controllers are widely used in industry for drives. In many industrial processes accurate speed control associated with good speed holding capability in the presence of load disturbance is essential to ensure product quality.
The speed controller converts the speed error in a torque reference value (or current reference value). Keeping torque and current within predetermined boundaries is achieved by limiting the output of the speed controller.

Paper [132] solves the control problem of SRMs without velocity measurements. The controller is composed of a loop in the mechanical dynamics which consists of a PI\(^2\)D controller and a tracking controller closing an inner loop with the stator currents dynamics.

Paper [133] presents a high performance current controller has for SRM drives. Based on the online estimated back EMF and incremental inductance, back-EMF decoupling and adjustable PI gain techniques are used in the current controller. The proposed current controller maintains a constant bandwidth over the full operating range.

The simplified PI controller can be seen as Figure 13.

![Block diagram of the simplified PI controller](source: Z. Lin, D. Reay, B. Williams, and X. He)

The PI gains are designed based on the desired system bandwidth. The transfer function of the PI controller is

\[
\frac{V^*(s)}{i_{err}(s)} = \frac{K_p s + K_i}{s}
\]  

(1)

Where \(K_p\) is the proportional gain and \(K_i\) is the integral gain.

The open-loop transfer function of the system, including the gain of the power converter \(K_c\), is

\[
\frac{i_{ph}(s)}{i_{err}(s)} = \frac{K_p (s + K_i/K_p)}{s} K_c \frac{1}{L_s (s + R_s/L_s)}
\]

(2)

Using the controller to cancel the motor pole

\[
\frac{K_i}{K_p} = \frac{R_s}{L_s}
\]

(3)

The closed-loop transfer function becomes

\[
\frac{i_{ph}(s)}{i_{DEMS}(s)} = \frac{K_p K_c}{L_s s + K_p K_c} = \frac{K_p K_c / L_s}{s + K_p K_c / L_s}
\]

(4)

The bandwidth of the closed-loop system is \(K_p K_c / L_s\), so if the desired system bandwidth \(\omega_{bw}\) is defined, then the proportional and integral gains are

\[
K_p = \frac{L_s \omega_{bw}}{K_c}
\]

(5)
Simulation of Switched Reluctance Motor and Control Based on MATLAB Environment

\[ K_t = \frac{R_s \omega_{bw}}{K_e} \]  

The incremental inductance \( L_s \) varies with phase current and rotor position. For an adjustable gain PI controller, the proportional gain \( K_p \) is adjusted according to the estimated inductance using (5) and \( K_i \) is a constant which is calculated from (6).

(3) Tuning the speed controller

The tuning of electric drive controllers is a complex problem due to the many non-linearity of the motor, power electronic converter and controller.

In paper [134], an adaptive input-output feedback-linearization technique is used for speed and torque-tracking control of synchronous reluctance motor drive without mechanical sensor. This controller is capable of estimating motor two-axis inductances \( (L_d, L_q) \) simultaneously.

Paper [135] develops a simple controller for the SRM based on state-switching digital control. The concept of state-switching digital control is to control the motor state (speed) by applying a high or a low energy pulse-above and below the desired steady state of the motor. Such a controller can be implemented in low-complexity analog circuitry. This paper presents two methods of motor control: one for single speed applications and another for variable speed applications.

![Figure 14. Block diagram of the variable-speed controller based (source: S. M. Lukic, and A. Emadi) [135]](image)

Block diagram shown in Figure 14 shows the layout of the controller. The hysteresis current controller is used as in previous implementation. The speed controller is a sliding mode control based controller that acts on the reference current based on the sign and the magnitude of the speed error.

2.8.5.3 Torque Control

Torque control constitutes the main control block in drives to obtain the desired high bandwidth in torque and speed responses.

(1) Instantaneous torque control

In the instantaneous torque control strategies, the current references are computed at each sample time, according to the total torque reference and the rotor position.

The overall block diagram of the controller is shown in Figure 15. An encoder is used to continuously feedback the rotor position to the controller. The torque is regulated in the inner control loop, whereas the speed is controlled in the outer loop through an IP controller. The speed
error signal generates the total torque command that is distributed over the phases and then converted to current references. The desired current is compared with the actual current, and the generated switching pattern is fed to the power converter (included in the SRM block).

Figure 15. Instantaneous torque control strategy (source: H. Hannoun, M. Hilairet, and C. Marchand) [138]

An on-line instantaneous torque control technique for a SRM operating in the saturation region is presented in paper [136]. The proposed methodology is realised via the control of the instantaneous output torque of each excited phase by regulating its associated co-energy to follow a co-energy profile.

(2) Average torque control

The average torque control strategy is also called “square wave control”

The block diagram for average torque control is shown in Figure 16. The structure is the same as in instantaneous torque control (same IP speed controller as mentioned in instantaneous torque control strategies, same hysteresis current controller). The main difference is located in the transformation from torque to current reference. In this strategy, the total reference torque produced by the speed controller is considered as an average torque over one conducting period. The torque translation into a current reference is located in a lookup table. Linear data interpolation is performed online to compute the optimal control parameters depending on the operating point.

Figure 16. Average torque control (source: H. Hannoun, M. Hilairet, and C. Marchand) [138]
A bearing-less SRM has a complicated nonlinear character; therefore, its control strategy is very important to a stable operation. Paper [137] proposes a new control strategy named the least magneto-motive force control strategy which can enhance the availability of winding currents and decrease the torque ripple and stator vibration.

A speed control strategy for a wide speed range operation has been proposed in paper [138]. Based on average torque control, the control parameters are optimized according to different criteria.

Paper [139] presents an innovative torque control strategy for a SRM operating in continuous-conduction mode (CCM). The proposed strategy was first designed to control the torque in discontinuous-conduction mode and then extended to operate in CCM as well. With CCM, the torque can be increased at high speed without modifying the number of turns, the source voltage, or the converter; it is achieved through the control.

Paper [140] proposes the use of iterative learning control in designing a torque controller for SRMs. The results show very good average as well as instantaneous torque control.

Paper [141] presents a SRM model based on an invertible expression representing the torque-phase current relationship. The model can be useful for real-time control in high-performance applications when the command current is derived from the torque command.

Paper [142] proposes a control scheme for rotating and levitating a 12/8 bearing-less SRM. The motor average torque and radial force are independently controlled with hybrid excitations in main windings and levitation windings.

2.8.5.4 Other Control Methods

Paper [143] proposes a passivity-based controller for sensor-less SRM drive systems. By using the proposed controller, the drive systems can achieve fast transient responses, good load disturbance responses and good tracking responses.

In paper [144], one bearing-less 8/6 SRM with simpler single layer of winding structure has been developed. Its main characteristic is that the total winding number of motor is decreased from eight to six. Its special driving theory and speed regulation technique of the motor by applying three phase windings have been introduced.

A new sensor-less control method based on phase inductance vectors of SRM is presented in paper [145]. This sensor-less method eliminates the problem of starting hesitation and offers adequate accuracy in rotor position estimation even in slightly inductance asymmetric conditions, which can drive the SRM from standstill to high speed operation smoothly.

Paper [146] has presented the development and control of a three phase SRM drive constructed using a three phase IPM. From the measured motor winding inductance profile and the ratings, the effects of winding inductance and back EMF on the current control behaviour are comprehended, and the proper tuning for commutation turn-on/turn-off angles and the DC link voltage boosting are made to yield satisfactory driving performance under wide operating conditions. And, a speed control scheme consisting of a PI feedback controller and a simple output feedback LMFC is designed for obtaining good speed tracking and regulation responses.
In paper [147], the control of SRMs is approached from a passivity-based control perspective. The proposed controller solves the torque/speed/position tracking problem by exploiting the passivity properties of the motor.

The suggested method in paper [148] is based on the optimal control of flux linkage, through the firing angles, according to load torque requirements and depending on rotor speed. A controller that determines online the optimal turn-on and turn-off angles is proposed.

The use of embedded Runge-Kutta methods for the time-domain simulation of a dynamic finite-element model of a SRM is discussed in paper [149], along with the features of embedded Runge-Kutta methods for the numerical solution of this model.

Paper [150] presents a split AC drive system for a novel two phase flux-reversal-free-stator SRM, and it has a single-switch per-phase topology.

In paper [151], a control scheme for self-bearing operation of a 12/8 pole SRM drive is proposed. The rotor needs only one bearing for rotation and constraining the axial movement. The other end can move freely in the radial direction but is balanced with the radial force produced by the motor.

Paper [152] presents a control scheme that allows minimization of DC-link capacitance in SRM drives. In SRMs, the demagnetization energy of the outgoing phase causes a voltage increase in the DC-link. Therefore, large DC-link capacitors are required in conventional drives to absorb this energy to avoid over voltages.

A new sensor-less control scheme for the SRM drive at low speed is presented in paper [153].

### 2.8.6 Converter Structures for Switched Reluctance Motor

The block diagram of a conventional SRM converter is shown in Figure 17. It can be divided into: utility, AC/DC converter, capacitor network, DC/DC power converter and SRM.

![Converter Structures for Switched Reluctance Motor](source: J. W. Ahn) [40]

The converter for SRM drive is regarded as three parts: the utility interface (Figure 18), the front-end circuit and the power converter (Figure 19). The front-end and the power converter are called as SRM converter.
2.8.6.1 Utility Interface

The main function of utility interface is to rectify AC to DC voltage. The line current input from the source needs to be sinusoidal and in phase with the AC source voltage. The AC/DC rectifier provides the DC bus for DC/DC converter. The basic, the voltage doubler and the diode bridge rectifier are popular for use in SRM drives.

![Utility Interface Diagrams](image)

Figure 18. Utility interface (source: J. W. Ahn) [40]

2.8.6.2 Front-end Circuit

Due to the high voltage ripple of rectifier output, a large capacitor is connected as a filter on the DC link side in the voltage source power converter. This capacitor gets charged to a value close to the peak of the AC input voltage. As a result, the voltage ripple is reduced to an acceptable value, if the smoothing capacitor is big enough. However, during heavy load conditions, a higher voltage ripple appears with two times the line frequency. For the SRM drive, another important function is that the capacitor should store the circulating energy when the phase winding returned to.

In paper [154], the development and control for a SRM drive with front-end switch mode rectifier are presented, and good motor driving performance and line drawn power quality are obtained.

Paper [155] presents a characteristic analysis of the SRM considering freewheeling diode and DC-link voltage ripple by using time-stepped voltage-source finite-element method in which the magnetic field is combined with the drive circuit.
2.8.6.3 Power Converter

It is necessary to know the characteristics of the DC supply and of several types of power electronics switches. A battery can supply and receive power. It is a reversible voltage source. The winding of an electrical motor phase is a reversible current source. During its operation, the converter connects through these switches the sources ensuring and controlling the exchange of energy. In order to make these links, a certain number of rules have to be respected imperatively:

- A voltage source should not ever be short-circuited, but it can be opened;
- The circuit of a current source should not never be opened but it can be short-circuited;
- Two sources of the same nature should never be connected;
- Only a current source and a voltage source can be connected.

As an observation, a direct converter is an electric circuit made only of switches. It is unable to store energy, the energy transfer being carried out directly from input to output. If the losses in the converter are neglected, input and output power are equal at each instant. The current control in SRM is realized by chopping the supplied voltage among three values: +V_{dc}, 0, and -V_{dc}. Since the torque of a SRM is independent of the excitation current polarity, the direction of the current flowing into the phase windings will be the same in all the cases. Motoring and braking in four-quadrant operation are made in the same way, the difference being given by the instant when the voltage is applied, in accordance to the intervals and switching angles developed previously. The DC source may be a battery but usually is a rectified ac supply with a filter to provide a DC input source to the SRM converters.
In Figure 20, by closing K1 and K3, and opening K2 and K4, the SRM phase is supplied with fully positive voltage provoking a rise of the current, corresponding to the inrush interval (1). The chopping interval consists of a hard chopping, corresponding to a switch of the voltage between fully positive (2) and fully inverted voltage supply (2’). The sub-interval (2) is identical with the inrush interval, and the (2’) sub-interval is realized by closing K2 and K4, and opening K1 and K3. The freewheeling interval (3) is obtained by closing K1 and K4, and opening K2 and K3. The fully inverted voltage is obtained in a similar way as sub-interval (2’), corresponding to the extinction interval (4).

Paper [156] detailed discusses the principle of power converter for a SRM.

Paper [157] presents a SRM drive powered by a three phase single switch mode rectifier. The digital controls of both power stages are realized in a common DSP.

Paper [158] presents a novel passive boost power converter and its analysis for a three phase SRM drive. The proposed simple passive circuit adds three diodes and one capacitor to the front end of a conventional asymmetric converter in order to obtain a high negative bias. Based on this passive power network, the terminal voltage of the converter side is at general DC link voltage level in parallel mode and is up to a double DC link voltage level in series mode. As a result, it can suppress the negative torque generation from the tail current and improve the output power. It may increase cost for the proposed converter. However, it has a simple structure and is easy to install into the original converter.
A new low-cost, brushless variable-speed drive requiring only a single controllable switch and a diode single switch converter is proposed in paper [159]. The drive system is realized using an asymmetric two phase SRM, the proposed converter, and DSP controller.

Paper [160] presents a new configuration of power converter which is quasi-three-level converter for SRM drives to reduce current rising and falling times. The system allows reduction of the detrimental impact of the commutation processes in motor winding on overall motor performance through enabling reconfiguration of windings connection during operation of motor. Shorter time of commutation, which is the main characteristic of the system, increases the motor average torque particularly in range of operation with high rotational speed.

The novel converter topology has been proposed in paper [161] for SRM. The proposed converter circuit is based on two pack switch modules and bifilar windings. In comparison with traditional SRM converters, it only requires the half number of two pack switch modules. Furthermore, this converter has the simple topology and can operate under charging, freewheeling, and discharging modes.

Paper [162] proposes an optimization method for a SRM fed by an asymmetric bridge converter. The optimized SRM produces 2.5 times larger minimum torque than that of the initial motor in the low speed range.

Paper [163] investigates the energy conversion efficiency of SRMs with zero-voltage loop current commutation. Zero-voltage loop commutation in SRM operation can result in a significant improvement of their performance by lowering the flux linkage peaks and harmonic magnitudes of the magnetic flux densities within the core of the SRM.

A new switching pattern generating algorithm for a single-bus star-connected SRM drive was introduced in paper [164]. This method enables a (n+1) phase asymmetric inverter to control an n-phase SRM in four-quadrant modes of operation.

In paper [165], a thermal model for power converter used in SRM drive under constant convective heat transfer has been introduced. This model can predict the temperature rise distribution in power converter, optimize heat sink geometry and the placement of power components.

SRMs are very suitable for high speed applications. However, when running at high speeds, rapid braking becomes difficult because the regeneration energy may increase the DC link voltage to a critical level if a diode rectifier bridge is used for AC-DC conversion. Paper [166] investigates the relationship between the regeneration energy and the DC link voltage and proposes an electric braking scheme employing two phase excitations. During braking, instead of regenerating the excessive rotor kinetic energy back to the DC link, the energy is dissipated in the stator winding resistance. Therefore, the rotor can stop safely within a short time.

Paper [167] presents a characteristic analysis of SRM considering hard chopping and DC link voltage ripple by using time-stepped voltage source finite element method in which the magnetic field is combined with drive circuit.

A power converter with the capability of providing increased demagnetization voltage is presented in paper [168]. A converter with high demagnetization voltage was then derived from this basic converter.
Paper [169] presents a hybrid sensor-less controller used with both the classical eight-switch converter and a reduced six-switch converter topology for SRM drives.

Paper [170] presents a characteristic analysis of a wye-connected toroidal winding SRM driven by 6-switch converter.

A novel four-level converter and instantaneous switching angle detector for a high speed SRM are proposed in paper [171].

Paper [172] presents the development of a front-end converter and its control for a battery powered SRM drive. In motoring mode, the converter is operated as a DC-DC boost converter to establish dynamically boostable and well-regulated DC-link voltage from battery. In idle charging mode, the proposed front-end converter is arranged to act as a buck-type switch-mode rectifier for charging the battery with good line power quality.

A technique has been presented in paper [173] and demonstrated for driving the gates of the power devices in a combined asymmetric half bridge converter supplying two phases of a SRM.

**2.9 Faults Diagnosis**

The analysis of the SRM faults is essential to the study of the fault tolerance capability of these motors in critical applications. Typically, SRMs are a single excited motor with phase coils diametrically wounded around opposite stator poles. The phase excitation makes the rotor poles to be aligned with the produced flux lines along that phase in order to minimize the reluctance of the magnetic path, generating the reluctance torque. Owing to these characteristics, the magnetic interactions between motor phases are negligible in SRM, and a fault occurrence in one phase does not affect the remaining motor phases. However, their electromagnetic and mechanical behavior is deteriorated, and the rotor is subjected to unbalanced forces.

Paper [174] analysis the influence of rotor structure on fault diagnosis indices variations for SRMs.

**2.9.1 Power Converter Fault Diagnosis**

One of the most susceptible parts of an electric motor drive is the power converter. As a result, open- and short-circuit faults in a power switch can have a serious impact on the drive performance. Open-circuit fault detection and localization of a specific power switch present some difficulties since an open circuit fault in any of the two power switches, associated to the same motor phase, causes identical phase current profiles. On the other hand, a short circuit in a power switch can cause an excessive electric current amplitude, which may lead to the disconnection of the affected motor phase because of the action of overcurrent protection devices.

Paper [175] presents a new fault diagnostic technique applied to SRM drives, based on the analysis of the power converter supply current. A fault is detected when the measured amplitude of the DC bus current differs from its expected amplitude, assuming normal operating conditions. The information about phase currents amplitudes and the control commands of all power switches permit to easily estimate the amplitude of the power converter supply current, since an asymmetric bridge converter is used.

In paper [176], a new algorithm for real-time diagnosis of power converter faults in SRM drives is proposed. The presented technique uses the measured phase currents only, which are already
available for the drive control. The proposed algorithm effectively detects the inverter faulty phase and is capable of localizing the faulty power switch.

Paper [177] provides a systematic classification for the existing position sensor-less techniques used in SRM drives. Their performances are analyzed under phase fault condition. A family of fault resilient strategies for position sensor-less techniques of SRM drives under single and multiphase faults is presented.

Paper [178] presents a new configuration for dual-channel SRM called as decoupled DCSRM under normal and open-circuit fault operations. To achieve fault-tolerant operation, a control strategy of open-circuit faults for the DDCSRM drive is presented. The key of the fault-tolerant control strategy is to maintain the rotor speed as the normal motoring operation.

Paper [179] describes four main fault types of the asymmetric bridge power converter in SRM drive on power transistors. Two on-line fault diagnosis methods for power transistors in the power converter are proposed. The principle of the proposed diagnosis methods is to detect the real time current state from some particular positions, and then obtain the diagnosis result and the fault location by logical judgment. One fault diagnosis method is proposed using single current sensor monitoring the chopped bus current; the other method is using dual current sensors scheme monitoring the upper freewheeling bus current and excitation bus current.

Paper [180] takes an in-depth look at winding short circuits in SRM.

The goals of paper [181] are the systematic classification of all electrical faults, for short and open circuits, in the SRM drive (excluding the controller itself) and the investigation of fault patterns and possible remediation.

### 2.9.2 Eccentricity Faults Diagnosis

Eccentricity faults are among common types of fault in SRMs, they have effects on magnetic behavior of the motor. Eccentricity exists in a motor when there is an uneven air-gap between the stator and the rotor poles. These faults yields bearing damages, unbalanced magnetic pull, excessive noise and vibration, and consequently, it may cause rotor poles rubbing against the stator poles, resulting in gradual deterioration of the motor.

Paper [182] presents a new method for non-invasive diagnosis of static, dynamic, and mixed eccentricity faults in SRMs. In this method, first, occurrence of the fault and its location are detected by utilizing eccentricity level detection pattern. Afterward, a new index to precisely determine the fault level is introduced. Then, a novel strategy based on the proposed pattern and index is offered to detect the type of eccentricity as well as the exact location of the faulty phase.

Paper [183] presents a comprehensive method for eccentricity fault diagnosis in SRM during offline and standstill modes. In this method, the fault signature is achieved by processing the differential currents resulted from injected high frequency diagnostic pulses to the motor windings.

In paper [184], a comprehensive method for eccentricity fault diagnosis in SRM based on stator voltage signature during offline and standstill modes is presented. This sensor-less method is able to detect occurrence, location, direction, and severity of the eccentricity fault in SRM.

A modular stator SRM for fault tolerant drive systems is proposed in paper [185]. Owing to the particular construction of the stator there is no mutual coupling between adjacent phases. Hence,
the motor can work also when a part of the coils is faulted and the faulted modules can be replaced without uncoupling the motor from the load or gearbox.

Paper [186] describes a 2-D finite-element analysis of an 8/6 SRM with static eccentricity. It describes the influence of the eccentricity on the static characteristics of the motor and shows how to obtain flux lines, flux density distribution, and the flux-linkage/rotor angular position characteristic of the motor in both healthy and faulty conditions, as well as the static torque profiles of phases for different degrees of eccentricity.

Paper [187] presents a novel method for diagnosis of eccentricity in a SRM. The method employs 2-D finite-element analysis to calculate mutual fluxes and mutually induced voltages in an 8/6 SRM.

Paper [188] describes a study into the effects of rotor eccentricity on the torque in a four-phase 8/6 SRM.

Paper [189] investigated rotor eccentricity effects on SRM and reduction of these effects by winding method.

### 2.10 Torque Ripple Minimization

In order to increase torque and power densities of SRMs, as for reducing vibration and acoustic noise, some methods as optimizing the motor structure, optimizing the control strategies, and developing new motor structures can be employed.

Paper [190] presents a control technique for torque ripple minimization in the SRM drive, based on a torque-sharing function concept. In the proposed method, the reference torque is directly translated into the reference current waveform using the analytical expression.

The method in paper [191] using punching holes in rotor poles to modify the waveforms of flux as well as derivatives of inductances with respect to rotor position is proposed.

In paper [192], based on the output torque analysis at the rotor position for the given air-gap, the air-gap is modified to reduce the torque ripple.

In paper [193], a SRM design that improves torque output by using segmented rotor topology with five phases is designed and evaluated.

Paper [194] presents a method to reduce torque ripple of SRM by relocation of rotor moulding pins. The obtained results show that the torque ripples of the two motors are lower when moulding pins are closer to the rotor position.

Paper [195] presents the speed ripple and vibration reductions for a switch mode rectifier fed SRM drive via intelligent current profiling approach.

In average torque control, the current references of two subsequent phases are designed independently, i.e., the current profile between two subsequent phase excitations is not controlled. Therefore, high torque ripple will occur during commutation. Also, the flat top of the current shape is expected to produce torque ripple.

Paper [196] presents the performance of an instantaneous torque control method. The idea of the control method implemented in this work is to define the commutation angle, at which two adjacent
phases can produce the same torque for same current. Based on the commutation angle, specific current references for commutation are designed, which is theoretically able to eliminate the torque ripple due to the torque dip.

A novel Lyapunov function-based direct torque controller for minimization of torque ripples in a SRM drive system is reported in paper [197]. The direct torque control scheme avoids the complex process of torque-to-current conversion as required in indirect torque control scheme. The proposed controller is intended to take care of the nonlinear system dynamics of magnetic characteristics associated with accurate torque control using direct torque control scheme for the SRM drive system. In the Lyapunov function-based controller, the feedback gain is varied using a heuristic technique.

In paper [198], an optimisation techniques for a hysteresis current controller to minimise torque ripple in SRM is presented.

A novel flux-linkage controller using sliding mode technique with integral compensation (SM-I) is proposed in paper [199] for torque ripple minimization of a SRM. The proposed SM-I controller inherits the advantages of PI and conventional SM controller.

In paper [200], the geometry for low torque ripple is researched and a SRM having notched teeth is proposed.

Paper [201] introduces five new optimization procedures for the minimization of the torque ripple in the SRM. These new procedures are based on the optimization of the phase-current profile.

SRM torque ripple reduction scheme using a B-spline neural network is presented in paper [202].

Paper [203] describes a proposal for a new stator pole face having a non-uniform air-gap and a pole shoe attached to the lateral face of the rotor pole. These additions minimize the undesired torque ripple.

A single phase SRM drive system is presented in paper [204], which includes the realization of a drive circuit for the reduction of torque ripple and PF improvement with a novel switching topology. The proposed drive circuit adds one switch and one diode, which can separate the output of the AC/DC rectifier from the large capacitor and supply power to the SRM alternately.

The purpose of paper [205] is to perform a multi-objective optimization in a 4/2 SRM aiming both to maximize the mitigation of the torque ripple and to minimize the degradations of the starting and mean torques.

A novel and simple nonlinear logical torque-sharing function for a SRM drive is proposed in paper [206]. This novel scheme using nonlinear TSF manipulates currents in two adjacent phases during commutation, so that efficiency and torque ripple in a SRM drive can be considerably improved.

Two improved torque-sharing functions for implementing torque ripple minimization control are presented in paper [207].

2.11 Vibration and Acoustic Noise

Vibration and acoustic noises are viewed as a drawback in SRMs, which prohibit their widespread use in noise sensitive applications.
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Paper [208] describes an environmental and life cycle cost (LCC) analysis of one SRM drive and two inverter-fed induction motor drives. Environmental impact and LCC were evaluated according the Methodology for the Eco-design of Energy-Using Products and accounting different operation conditions. The SRM drive was found to have less environmental impact than were the IM drives which includes noise level and life cycle cost etc.

Paper [209] uses a multi-physic analysis to compare mechanical vibration between a double-stator SRM (DSSRM) and a conventional SRM with the same outer diameter, yoke thickness, and output power. It has been shown that not only is the radial force amplitude smaller in the DSSRM, the force distribution in this motor tends to offer a lower vibration level.

Prediction of acoustic noise distribution generated by electric motors has become an integral part of design and control in noise sensitive applications. In paper [210], a fast and precise method for prediction of acoustic noise in SRM is presented. Using this method, acceleration of the probing network on the stator frame can be calculated from the rotor position and phase current/voltage waveforms. Consequently, electromagnetic and transient structural finite-element analysis can be bypassed for their low computation efficiency. With the acceleration of the probing network available, full structural response can be expanded for BEM, which allows for effective computation of acoustic noise in SRM drives.

Paper [211] presents a multi-physics analysis to predict the acoustic radiation properties of a SRM. The proposed method uses a 2-D finite-element model of the motor to simulate its magnetic properties and a multi-physics mechatronic model of the motor and controls to simulate operating conditions.

Paper [212] presents an acoustic simulation of a special SRM with asymmetric pole geometry to improve the start-up torque.

In paper [213], electromagnetic interference in operated SRM drive is analyzed, which includes mechanism of electromagnetic interference (EMI) noise generation in SRM drive, performance comparison of noise source internal impedance extraction methods. Moreover, the solution of SRM drive EMI noise is optimized by making use of economic integration based decision making parameters modeling method.

Paper [214] presents a single phase SRM with skewed stator and rotor so that the acoustic noise and vibration have been significantly reduced. In this paper, the distribution of the RF with respect to the skew angles is analyzed through the finite-element method simulation to design a single-phase SRM with the significantly reduced vibration and noise.

Paper [215] describes the design and the placement of piezoelectric actuators on SRMs by means of a genetic algorithm for the purpose of reducing stator vibrations.

Paper [216] presents a powerful new design aspect to reduce acoustic noise and vibration of electromagnetic origin for SRMs, by introducing improved slot wedges referred to as “structural stator spacers.”

In paper [217], a hybrid excitation method with C-dump inverter is proposed to reduce vibration and acoustic noise in the SRM drive.

Paper [218] deals with the vibration analysis and the optimal control for the vibration reduction in a SRM.

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Paper [219] introduces a simple and non-destructive method for the measurement of Young’s modulus, it is then used in a finite-element program to determine the resonant frequencies of SRM stator vibration.

Paper [220] presents a thorough numerical study of vibration analysis in electric motors, with particular application to SRMs, using 3-D finite-element analysis methodology.

A new experimental study to reduce the acoustic noise of the SRM has been presented in paper [221].

In paper [222], a simulation model to predict the transient vibration of SRMs is developed. The vibration prediction model is built based on the detailed normal force versus phase current and rotor position lookup table using finite-element calculations.

A comparative study of vibration and acoustic noise reductions via electronic switching controls for SRM is presented in paper [223].

Paper [224] presents a novel radiating rib structure in SRMs, because the radial vibration of the stator is the primary source of the acoustic noise of SRMs, the modal analysis of the stator vibration is an important and effective way to reduce the acoustic noise.

Paper [225] presents two vibration control approaches using piezoelectric inserts applied to a SRM in order to reduce acoustic emission.

Paper [226] compares and investigates the vibration and noise characteristics through simulations and experiments of 12/8 and 6/4 SRMs.

Paper [227] describes an investigation into the reduction of vibration and acoustic noise in SRM in radial force excitation and frame transfer function aspects.

Paper [228] presents a scheme that produces a controlled radial force for a 12/8 SRM.

In paper [229], a sinusoidal current excitation scheme is proposed for the torque and radial force control of a 12/8 SRM.

2.12 Modeling Methods

Paper [230] reviews the technology status and trends in SRMs. It covers the various aspects of modeling, design, simulation, analysis, and control.

In paper [231], a novel new grid-diamond search algorithm is proposed and adopted to optimize parameter of an improved least square support vector motor regression of a nonlinear model of SRM.

Paper [232] presents an extended field reconstruction method (FRM) to model a SRM, which is set apart from other electric motors by its double-saliency and magnetic saturation. FRM can significantly reduce the computational time by utilizing a small number of static magnetic field snapshots to establish the basic functions which are then used to reconstruct the magnetic field with high accuracy. In this paper an extended version of FRM is introduced within which effects of magnetic saturation and double saliency are taken into account.
Paper [233] develops and compares different techniques for the modelling of a SRM in view of its nonlinear magnetisation characteristics due to the doubly salient structure.

A direct field-circuit-motion coupled model combined with finite-element analysis is presented in paper [234] to simulate the steady operating state of SRMs and to calculate the dynamic currents and torques of the motors.

Paper [235] discusses the simulation of SRM drives using 2-D bi-cubic spline.

In paper [236], the experimental design method is applied to the construction of a response surface based on diffuse elements as preliminary steps in the optimisation process of the magnetic torque of a SRM.

In paper [237], sequential approximate optimisation has been applied to the design-optimisation of SRM.

Paper [238] models the magnetic coupling effects of phase windings in a typical two-phase excited 6/4 SRM.

A design methodology is presented in paper [239] for a low duty cycle SRM. A low duty cycle motor can withstand higher current density, since winding temperature cannot rise instantaneously to the steady-state value due to the gradual heating of the thermal masses.

Paper [240] sets forth a nonlinear average value model of a SRM.

Paper [241] presents a dynamic two-phase excitation model of the SRM.

A novel invertible generalized flux/current SRM model based on the Fourier series expansion is presented in paper [242].

Paper [243] proposes two distinct numerical simulation methods using finite-element time-step analysis for predicting the current waveform of a SRM drive and explains them in detail.

An auto-calibrating inductance model for SRM drives is presented in paper [244].

In paper [245], the continuous mode for SRM is described.

Paper [246] describes a neural network method for optimal design of a SRM.

A novel online-modeling scheme for the SRM using a B-spline neural network is proposed in paper [247].

Paper [248] presents a new rapid nonlinear simulation method for SRMs.

Paper [249] presents a new analytical model for SRMs. The model uses four coefficients, which are rotor position dependent and calculated from the flux-current-angle data using numerical curve fitting with least squares method.

Paper [250] develops a dynamic analytical circuit model to simulate the performance of SRMs. The model expresses flux linkages as multiple decoupled one-argument functions, either current dependent or rotor position dependent, instead of one two-argument function dependent on both current and rotor position.
Paper [251] presents the use of Taguchi methods in optimizing a SRM for applications requiring fast actuation.

2.13 Application

SRM system is a mechatronic device that has been developed for many years. The iron core of the stator and the rotor in the SRM are laminated by the magnetic sheet steels, which are the structure of the salient pole. There is a centralized coil in each stator pole. The motor is supplied with the unipolar current by the unipolar power converter. It has the advantages of a firm structure of the motor without brushes on the rotor and the firm structure of the unidirectional power converter without the “direct-short circuit” fault in the bidirectional power converter. It also has an advantage in the implementation of the fault-tolerant control. The system has a good ability for fault-tolerant control with independence on the magnetic flux paths of the motor and on the main circuit of the power converter. The reliability of the SRM system is higher than that of other types of the motor system. It had been applied as a motor in many situations, such as in electric vehicles, in high-speed drives, in small domestic appliances, in fans, and in pumps.

Paper [252] [253] present three criteria for evaluating the motoring operations of SRM drives for electric vehicles (EVs). They imply motoring torque, copper loss, and torque ripple, respectively. By using three weight factors and three groups of base values, the optimization function with multiple objectives has been developed. The optimal control method for the best motoring operation of SRM drives in EVs has been proposed.

In paper [254] [255] [256] [257] [258] [259], it has been shown that a SRM can be designed to be competitive to the IPM motor employed in a HEV in the point of view of torque density, efficiency, and torque-speed range. It was shown that torque can be increased as the number of poles is increased. It is also found that the fabricated SRM has a good correspondence to the designed value in the point of view of inductances and efficiency in light load tests.

Paper [260] develops an integrated driving/charging SRM drive for electric vehicles using off-the-shelf three phase intelligent power modules. Its front-end DC/DC boost converter is formed by the remaining one leg to boost the DC link voltage from a battery. Proper current and speed control schemes are designed to yield satisfactory driving performance.

Paper [261] offers an in-depth analysis of the drive dynamics during motoring and generating modes of operation for electric car.

SRMs with a higher number of rotor poles offer better static torque capability with lower torque ripple for steady-state operation as compared to conventional configurations. Owing to the higher torque production capability with lower ripple, a SRM with a higher number of rotor poles is a potential candidate for traction applications in hybrid and plug-in hybrid electric vehicles. Paper [262] [263] [264] [265] [266] present the application of the SRMs with a higher number of rotor poles in electric vehicles. And the results show the proposed motor has been able to ensure enough mechanical strength to operate at the required high speed and achieve higher torque and power densities compared to existing motors.

Paper [267] presents a compact battery-powered SRM drive for an electric vehicle with voltage-boosting and on-board power-factor-corrected-charging capabilities.

In paper [268], it proposes robust nonlinear force controllers for a SRM electromechanical brake system which is a promising replacement for hydraulic brakes in the automotive industry.
Paper [269] offers a comparison of two motor technologies, switched reluctance and permanent magnet brushless, for electromechanical brake system.

Paper [170] presents a novel three phase SRM drive with integrated charging functions (including internal combustion engine and grid charging) for plug-in hybrid electric vehicles.

Paper [271] describes a comparative study allowing the selection of the most appropriate electric-propulsion system for a parallel hybrid electric vehicle (HEV).

Paper [272] presents a detailed investigation of the performance indices for bipolar SRM drives for automotive applications.

Paper [273] presents two three phase SRM systems. One is the dual motors drive for the electric locomotive traction, the other is the variable speed generator system for wind power applications.

In paper [274], a power smoothing system, based on a SRM driving a flywheel, is presented.

Paper [275] presents test results of a flywheel energy storage system prototype with the SRM.

A control system for power smoothing using a SRM driving a flywheel is presented in paper [276].

A bearing-less switched reluctance generator is developed in paper [277], which is operated in full-period generating mode. The proposed operations of outputting electric energy and producing suspension force, supply a novel perspective for integrating the bearing-less technique with the generator.

The multichannel generator is a kind of special generator, which is developed to enhance power reliability in safety critical applications. Paper [278] compares the dynamic performance computation for a 12/8 dual-channel switched reluctance generator under single- and dual-channel operation modes.

Paper [279] has examined the problem of choosing the firing angles for accomplishing optimal switched reluctance generator performance.

Paper [280] investigates the problem of optimal control for accomplishing maximum energy conversion in switched reluctance generators.

Paper [181] describes the design of a high speed three phase SRM to drive a compressor for the air management of a fuel-cell system for automotive applications. It shows that the SRM is an interesting solution for low-cost and robust high speed automotive applications compared with permanent-magnet synchronous motor structures even if the last ones are preferred for their high torque/weight ratio against a quite high price.

Paper [282] demonstrates three key technologies developed over the past few years that have resulted in tangible improvements in the performance of switched reluctance/generators as related to the above areas of interest. This paper intends to illustrate the new possibilities and remaining challenges in applications of switched reluctance in automotive industry.

Paper [283] presents a new class of brushless motor as an alternative to the permanent-magnet brushed motor used in the automotive industry.
Simulation of Switched Reluctance Motor and Control Based on MATLAB Environment

In paper [284], the optimum design approach for a two phase SRM compressor drive in a small refrigerator has been presented.

Paper [285] presents a new low-cost hybrid SRM intended for use in adjustable-speed pump drive systems. The motor is a single phase motor, driven by a unipolar converter, which uses both the reluctance torque and the permanent magnet interaction torque. Compared with conventional single phase SRMs, it has an increased torque density.

Paper [286] describes the developed three phase 6/8 poles switched reluctance external rotor motor drive for a fan in air conditioner. The three phase asymmetric bridge power converter was used in the drive system.

Paper [287], a modular stator construction is proposed for a SRM to be used for the air and water pumps of dialysis equipment.

Paper [288] presents the design, implementation and driving control of a SRM for driven cooling fan.

Paper [289] presents a low-cost energy-efficient variable-speed drive for high-volume applications, such as home appliances, fans, and hand tools.

Paper [290] presents the design, analysis and control of a high speed SRM with conical magnetic bearings for aircraft application. The details of modelling and controller design procedures for the conical magnetic bearings-rotor system based on a voltage controlled model without feedback loop are proposed.

In paper [291], a rapid-calculation nonlinear model of SRM drives system is modularly developed based on Dymola, a new object-oriented modeling software. The SRM drives system is constructed as a subsystem model for the aircraft electrical system model library.

A concept of an integrated and distributed inverter for SRMs is introduced in paper [292]. The application at hand is an outer-rotor direct drive designed for railway traction applications. The integrated inverter allows to increase the number of motor phases without increasing the number terminals. This simplifies the integration of the drive in the application. The high number of phases increases the redundancy of the drive. The phases are magnetically and electrically decoupled.

Paper [293] presents the study of the motor and the converter temperatures at rated and overload working conditions for traction applications.

In paper [294], a control strategy for reduced acoustic noise and sensor-less operation of a SRM is proposed for heating, ventilation, and air conditioning (HVAC) application, where the magnitude of the DC-bus voltage is controlled as a function of speed and the motor is operated in a single-pulse mode for all speed range.
3. Simulation of Switched Reluctance Motor

Most studies concerning dynamic simulation of switched reluctance machines have been achieved from the programming, either in C language, Fortran, and also employing differential equation-based languages such as ACSL. Even software designed to simulate electric network systems as the EMTDC and EMTP have been used.

This chapter presents a simulation model of a multiphase switched reluctance motor created in MATLAB environment. First, the detail mathematical model of the SRM is presented. Next, different steps taken to simulate the dynamic model of the SRM is presented. Then this chapter presents the simulation results for the steady and dynamic behavior of the model, and the simulation results will be compared with the results in paper [295]. Finally, it gives the concluding remarks. Detail of the MATLAB coding is included in the Appendix B.

3.1 Mathematical Approach

An accurate analysis of the motor behaviour requires a formal, and relatively complex, mathematical approach. The instantaneous voltage across the terminals of a single phase of a SRM drive winding is related to the flux linked by the winding. The flux linkage is a function of two variables, the current $i$ and the rotor position (angle $\theta$). The mathematical model describes the equivalent circuit for one phase (Figure 21).

$$V = R i + \frac{d\lambda(\theta, i)}{dt}$$

(7)

Where $V$ is the applied phase voltage to phase, $R$ is the phase resistance, and $e$ is back EMF. Ordinarily, $e$ is the function of phase current and rotor position, and flux $\lambda$ can be expressed as the product of inductance and winding current:

$$\lambda(\theta, i) = iL(\theta, i)$$

(8)
And from (8) and (9), the function can be rewritten as:

\[ V = Ri + \frac{d\lambda}{dt} \frac{di}{dt} + \frac{d\lambda(\theta, i)}{d\theta} \frac{d\theta}{dt} \]  

(9)

The general torque expression is:

\[ T(\theta, i) = \frac{\partial \lambda(\theta, i)}{\partial \theta} \]  

(10)

In general, the dynamical model of a SRM is characterized by the rotor angular speed and angular position relationship:

\[ \omega = \frac{d\theta}{dt} \]  

(11)

\[ T - T_{\text{load}} = J \frac{d\omega}{dt} + F\omega \]  

(12)

Where \( T_{\text{load}} \) is the load electromagnetic torque, \( T \) is the rotor torque, \( \omega \) is the rotor angular speed and \( F \) is the friction coefficient.

It is a set of four non-linear partial differential equations. Its solution, neglecting the nonlinearity due to magnetic saturation as equation (8).

The function can be written as:

\[ V = Ri + L(\theta, i) \frac{di}{dt} + i\omega \frac{dL(\theta, i)}{d\theta} \]  

(13)

The average torque can be written depending on the number of phases of the SRM as:

\[ T = \sum_{\text{phase}=1}^{n} T_{\text{phase}} \]  

(14)

### 3.1.1 Linear Analysis of the Voltage Equation and Torque Production

A linear analysis assumes that the inductance is unaffected by the current, thus no magnetic saturation occurs. For the sake of simplicity it is also assumed that all the flux crosses the air-gap in the radial direction, the mutual coupling between phases may be ignored, and the effect of fringing flux around the pole corners is also negligible. In the linear region, the equation (8) is shown the magnetic characteristics.

The linear inductance profile \( L(\theta) \) with each phase inductance displaced by an angle \( \theta_s \) given by

\[ \theta_s = 2\pi \left( \frac{1}{N_r} - \frac{1}{N_s} \right) \]  

(15)

Where \( N_r \) and \( N_s \) are the number of rotor and stator poles, respectively.

When the motor has equal rotor and stator pole arcs, \( \beta_r = \beta_s \), one has the following angle relations

\[ \theta_s = \left( \frac{\pi}{N_r} - \beta_r \right) \]  

(16)
\[ \theta_y = \frac{\pi}{N_r} \]  

(17)

Which are indicated in Figure 22 shows the angle \( \delta \) corresponding to the displacement of a phase in relation to another, and given by

\[ \delta = 2\pi \left( \frac{1}{N_r} - \frac{1}{N_y} \right) \]  

(18)

Figure 22. Angle \( \delta \) corresponding to displacement of a phase in relation to another (source: R. Krishnan) [42]

Assuming the 6/4 SRM has the following parameters:

\( L_{\text{min}} = 8 \text{ mH}, \ L_{\text{max}} = 60 \text{ mH}, \) and \( \beta_r = \beta_s = 30^\circ \). Thus, from (16) and (17), it gets \( \theta_x = 15^\circ \) and \( \theta_y = 45^\circ \).

The electric equation of each phase is given by

\[ E = R_i + \frac{d\lambda_p(\theta, i_p)}{dt} \quad \text{with} \quad p = \{1, 2, 3\} \]  

(19)

While excluding saturation and mutual inductance effects, the flux in each phase is given by the linear equation

\[ \lambda_p(\theta, i_p) = i_p L(\theta) \]  

(20)

The total energy associated with the three phases (n=3) is given by

\[ W_{\text{total}} = \frac{1}{2} \sum_{p=1}^{3} L[i(\theta + (n - p - 1)\theta_p)]i_p^2 \]  

(21)

And the motor total torque by
The mechanical equations are

\[ T - T_{load} = J \frac{d\omega}{dt} + B\omega \]  
\[ \omega = \frac{d\theta}{dt} \]  

Where \( T_{load} \) is the load electromagnetic torque, \( T \) is the rotor torque, \( \omega \) is the rotor angular speed and \( B \) is the friction coefficient.

### 3.1.2 Nonlinear Analysis of Torque Production

The analysis of SRM made till now has avoided the question of the influence of the nonlinear, saturation characteristic of real magnetic steel. However, a proper understanding and handling of saturation is essential.

Such analysis is based on magnetization curves. A magnetization curve is shown in Figure 23.

![Magnetization curves of switched reluctance motor](source: J. W. Ahn) [40]

The difference between these characteristics and the ideal ones is obvious. The two most important magnetization curves, the “aligned” and the “unaligned”, can be easily seen on Figure 23. At the aligned position, the curve is similar to that of an iron-cored inductor with an air-gap. At low flux density, the curve is linear. The unaligned curve is straight because of the dominating large air-gap. The saturation effect is observed at current levels that are usually too high for normal operation and therefore the unaligned curve is assumed to be linear.
The nonlinear effect of the magnetic circuit is well seen in Figure 23. In the linear part at any position the co-energy, represented by the area below the magnetization curve, is equal to the stored field energy, $W_f$, represented by the area above the magnetization curve as (Figure 24):

$$W_f = W' = \frac{1}{2}L(\theta, i)i^2$$  \hspace{1cm} (25)

Where $L(\theta, i)$ represents the inductance at a particular current value and rotor position.

![Figure 24. Relationship between energy ($W_f$) and co-energy ($W'$) (source: J. W. Ahn) [40]](image)

The co-energy is defined:

$$W' = \int \lambda di$$  \hspace{1cm} (26)

The most general expression for the torque produced by one phase at any rotor position is given by the change in magnetic co-energy:

$$T = \left[ \frac{\partial W'}{\partial \theta} \right]_{i=constant}$$  \hspace{1cm} (27)

Under a constant phase current as shown in Figure 25, when the rotor and total flux linkage are shifted from A to B, the SRM exchanges energy with the power source; thus, the stored field energy is also changed. The limitation to a constant current is that mechanical work done during the shifting region is exactly equal to the variation of co-energy. At a constant current, if the displacement between A and B is AB, the variation of energy received from the source can be expressed as:

$$\Delta W_c = ABCD$$  \hspace{1cm} (28)

$$\Delta W_c = OBC - OAD$$  \hspace{1cm} (29)

Then the mechanical work can be written as:

$$\Delta W_m = T\Delta \theta = \Delta W_c - \Delta W_c = OAB$$  \hspace{1cm} (30)
By applying the co-energy method to each rotor position and for the whole range of phase currents, the instantaneous torque curves can be build. An important observation is that not all the supply energy is converted into mechanical work, some of it being stored in the magnetic field. This has an important effect on the rating of the controller and the need for filter capacitors.

When the rotor pole pair is exactly aligned with the stator pole pair for any current flowing in the phase, no torque is produced because the rotor is at a position of maximum inductance.

The torque in a SRM is composed of a sequence of impulses and the flux in each phase must usually be built-up from zero and returned to zero during each stroke. To achieve continuous control of the instantaneous torque, the current waveform must be modulated according to a complex mathematical model of the motor, as shown later. For an \( n \) phase and \( N_r \) rotor pole SRM, the torque averaged over one revolution and the efficiency, are:

\[
T_{\text{ave}} = \frac{n N_r W}{2\pi}
\]

\[
\eta = \frac{T_{\omega}}{T_{\omega} + n R I_{\text{RMS}}}
\]

Where \( n \) is number of phases, \( N_r \) is number of rotor poles, \( W \) is energy converted from electrical to mechanical in one “working stroke” and \( I_{\text{RMS}} \) is the root mean-square value of the current in one phase. The torque ripple \( T_r \) is:

\[
T_r = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{ave}}}
\]

Where \( T_{\text{max}} \), \( T_{\text{min}} \) and \( T_{\text{ave}} \) are, respectively, the maximum, minimum and average torque values.

### 3.2 Energizing Strategies

In chapter 2, there are several possible configurations to energize an SRM from a converter. The different energizing structures distinguish themselves by their number of semiconductors and passive components. They also depend on the number of phases and the way the stator coils are connected. The maximum control and flexibility is obtained, however, with the H-bridge asymmetric type converter shown in Figure 26. Each phase has two insulated gate bipolar
transistors (IGBTs) and two diodes. The number of semiconductors is the same as for an inverter of a synchronous machine. However, the structure is completely different. One can also notice that it is not possible to short-circuit the source because the resistance of the coils limits the current.

![Figure 26. H-bridge asymmetric converter (source: J. W. Ahn) [40]](image)

Since we stand in linear regime, the flux relation is given by

\[
\lambda(\theta, i) = iL(\theta, i)
\]  

(34)

The co-energy stays

\[
W_f = W' = \frac{1}{2}L(\theta, i)i^2
\]  

(35)

Resulting in a torque given by

\[
T = \frac{1}{2} \frac{d}{d\theta} i^2
\]  

(36)

Equation (36) shows that this converter is unidirectional in current because torque production does not depend on the current sign but only of \(dL/d\theta\) sign.

The reluctance of the flux path between the two diametrically opposite stator poles varies as a pair of rotor poles rotates into and out of alignment. The inductance of a phase winding is the maximum when the rotor is in the aligned position and the minimum when the rotor is in the nonaligned position. Since inductance is inversely proportional to reluctance, a pulse of positive torque is produced if a current flow in a phase winding increases as the inductance of that phase winding is increasing. A negative torque contribution is avoided if the current is reduced to zero before the inductance starts to decrease again. The rotor speed can be varied by changing the frequency of the phase current pulses while retaining synchronism with the rotor position.
3.3 Control Strategies

3.3.1 Voltage Switching

The conditions for voltage switching are:

- When $0^\circ < \text{Rotor angle } (\theta) < \text{Turn-on angle } (\theta_{on})$, then Voltage = 0;
- When $\text{Turn-on angle } (\theta_{on}) \leq \theta < \text{Turn-off angle } (\theta_{off})$, then Voltage = +V;
- When $\text{Turn-off angle } (\theta_{off}) \leq \theta < \text{commutation angle } (\theta_d)$ then voltage= -V.

The control takes place applying the voltage source to a phase coil at turn-on angle $\theta_{on}$ until a turn-off angle $\theta_{off}$. After that, the applied voltage is reversed until a certain demagnetizing angle $\theta_d$, which allows the return of the magnetic flux toward zero. To apply voltage V in one phase, the two IGBTs Q1 and Q2 in Figure 26 must be ON. On the contrary, to apply the -V voltage and assure the current continuity, the two diodes D1 and D2 are used.

3.3.2 Speed Control

Various control strategies exist in chapter 2. The PI controller is chosen for the switched reluctance motor speed loop regulation.

Proportional-integral (PI) controllers are widely used in industry for drives. In many industrial processes accurate speed control associated with good speed holding capability in the presence of load disturbance is essential to ensure product quality.

The speed controller converts the speed error in a torque reference value (or current reference value). Keeping torque and current within predetermined boundaries is achieved by limiting the output of the speed controller. The most commonly used speed controller for drives contains two separate control loops (Figure 27). The inner loop is responsible for the current control and incorporates a PWM hysteresis controller, activated by the error between set and measured motor current. The current reference is generated by the outer control loop, in which the error between reference and actual speed activates the proportional-integral (PI) speed controller.

![Figure 27. Speed control of SRM (source: J. W. Ahn) [40]](image-url)
3.3.3 Hysteresis Current Control

The hysteresis current controller is used for low and middle speeds because one has enough time to be able to control the phase current (Figure 27). What also permits to use this current control mode at low and middle speeds, is that the FEM does not take large values that come to impair the current shape.

3.4 MATLAB Modeling

In this chapter, based on the mathematical approach of SRM given in this chapter, a linear inductance profile based SRM with hysteresis current control and PI speed control was simulated by using MATLAB. The modeling system diagram please see Figure 1 and the control system diagram please see Figure 27.

3.4.1 Flow Chart

All the necessary mathematical equations which govern the behavior of SRM are already given. The sequences which are followed in this chapter is shown in the flow chart below:

![Flow chart of modeling of SRM using MATLAB](link)

i. Initialization: Value of all the motor parameters such as number of stator and rotor poles, stator arc angle, rotor arc angle, turn-on angle, turn-off angle, commutation angle, separation of subsequent angle etc. are defined. These constant values of the parameters can be changed for different motors or for different data sheets. Data sheet of the motor used for this work is given in the Appendix A.
ii. **Creation of multiphase angular profile:** To create different phase angle, MATLAB command `rem` is used and subsequent separation of angle for different phase is created in the model.

iii. **Creation of linear inductance profile:** The linearized inductance profile of SRM is used in this chapter.

ix. **Creation of multiphase voltage switching profile:** H-bridge asymmetric converter is used here.

x. **Creation of multiphase current and flux linkage profile:** The Euler’s method is used to implement the voltage, current and flux linkage relation.

xi. **Creation of the multiphase torque profile:** Depending on the varying slope of the inductance for varying angle, torque profile is created.

xii. **Creation of total torque profile of the motor:** A simple addition operation of all the individual phase torques was done to get the overall torque of the machine.

xiii. **Output speed profile:** Equation (23) shows the mechanical equations for SRM.

### 3.4.2 Motor Parameters

The motor parameters for this model simulation please see Appendix A.

### 3.4.3 MATLAB Code

The MATLAB code for all the simulation is given in Appendix B.

### 3.5 Simulation Results

Some of simulation results will be compared with the results in paper [295]. In paper [295], the SRM is simulated by MATLAB/Simulink, the difference of simulation results will be discussed.

Supposing an ideal inductance shape, simulation curves in Figure 29-34 illustrate when the SRM is energized by a voltage source. The control takes place applying the voltage source to a phase coil at turn-on angle $\theta_{on}$ until a turn-off angle $\theta_{off}$. After that, the applied voltage is reversed until a certain demagnetizing angle $\theta_d$, which allows the return of the magnetic flux toward zero.

- Figure 29 shows the simulation result of one phase voltage at $\theta_{on}=0^\circ$ and $\theta_{off}=30^\circ$ with open loop control;
- Figure 30 shows the simulation result of one phase voltage with open loop control in paper [295];
- Figure 31 shows the simulation result of one phase inductance at $\theta_{on}=0^\circ$ and $\theta_{off}=30^\circ$ with open loop control;
- Figure 32 shows the simulation result of one phase inductance with open loop control in paper [295];
- Figure 33 shows the simulation result of one phase current at $\theta_{on}=0^\circ$ and $\theta_{off}=30^\circ$ with open loop control.
- Figure 34 shows the simulation result of one phase current with open loop control in paper [295].
From Figure 29 and 30, it can be found that the phase voltage in paper [295] and this report are the same, it starts from 0, and between $\theta_{on}$ and $\theta_{off}$, the phase voltage is $+V$, and between $\theta_{off}$ and $\theta_d$, the phase voltage is $-V$, and the time from $\theta_{on}$ to $\theta_{off}$ is about 0.0025s, and the time from $\theta_{off}$ to $\theta_d$ is about 0.0025s.
From Figure 31 and 32, it can be found that the phase inductance in paper [295] and this report are the same, it starts from 0.008H, then it increases to 0.06H, and falling back to 0.008H.
From Figure 33 and 34, it can be found that the curve shape of phase current in paper [295] and this report are the same, but the value is a little difference, that’s because in paper [295], the simulation environment is based on Simulink, the algorithm, solver, and the stepper time in the Simulink is different from the MATLAB which is used for the simulation in this report.
To illustrate the importance of choosing an adequate $\theta_{\text{off}}$ angle, Figure 35-40 show the simulation results to set a higher $\theta_{\text{off}}$ value.

- Figure 35 shows the simulation result of one phase voltage at $\theta_{\text{on}}=0^\circ$ and $\theta_{\text{off}}=33^\circ$;
- Figure 36 shows the simulation result of one phase voltage in paper [295];
- Figure 37 shows the simulation result of one phase inductance at $\theta_{\text{on}}=0^\circ$ and $\theta_{\text{off}}=33^\circ$;
- Figure 38 shows the simulation result of one phase inductance in paper [295];
- Figure 39 shows the simulation result of one phase current at $\theta_{\text{on}}=0^\circ$ and $\theta_{\text{off}}=33^\circ$.
- Figure 40 shows the simulation result of one phase current in paper [295].

From Figure 35 and 36, it can be found that the phase voltage in paper [295] and this report are the same, it starts from 0, and between $\theta_{\text{on}}$ and $\theta_{\text{off}}$, the phase voltage is $+V$, and between $\theta_{\text{off}}$ and $\theta_d$, the phase voltage is $-V$. 
From Figure 37 and 38, it can be found that the phase inductance in paper [295] and this report are the same, it starts from 0.008H, then it increases to 0.06H, and falling back to 0.008H.
In Figure 39, we can observe that phase current does not reach a zero value anymore. Still, one can see in zone 1 that current starts decreasing less quickly because now we are in the decreasing region of the inductance, which did not happen in Figure 33. When in zone 2, since the phase voltage passes from -150 V to 0 V and so phase current starts increasing. At last, in zone 3, phase current starts decreasing because the inductance is constant.

From Figure 39 and 40, it can be found that the curve shape of phase current in paper [295] and this report are the same, but the value is a little difference, that’s because in paper [295], the simulation environment is based on Simulink, the algorithm, solver, and the stepper time in the Simulink is different from the MATLAB which is used for the simulation in this report.
Figure 41-47 show a set of simulation results using $\theta_{on}=0^\circ$, $\theta_{off}=30^\circ$, and with the motor functioning without load applied.

- Figure 41 shows the simulation result of one phase output torque at $\theta_{on}=0^\circ$ and $\theta_{off}=30^\circ$;
- Figure 42 shows the simulation result of one phase output torque in paper [295];
- Figure 43 shows the simulation result of total output torque at $\theta_{on}=0^\circ$ and $\theta_{off}=30^\circ$;
- Figure 44 shows the simulation result of total output torque in paper [295];
- Figure 45 shows the simulation result of motor speed at $\theta_{on}=0^\circ$ and $\theta_{off}=30^\circ$;
- Figure 46 shows the simulation result of motor speed in paper [295];
- Figure 47 shows the simulation result of one phase back EMF at $\theta_{on}=0^\circ$ and $\theta_{off}=30^\circ$.

From Figure 41 and 42, it can be found that the curve shape of phase torque in paper [295] and this report are the same, but the value is a little difference, that’s because in paper [295], the simulation environment is based on Simulink, the algorithm, solver, and the stepper time in the Simulink is different from the MATLAB which is used for the simulation in this report.
From Figure 43 and 44, it can be found that the curve shape of total torque in paper [295] and this report are the same, but the value is a little difference, that’s because in paper [295], the simulation environment is based on Simulink, the algorithm, solver, and the stepper time in the Simulink is different from the MATLAB which is used for the simulation in this report.

As expected, one can see in Figure 41 that the one phase torque and the total torque are always positive, as shown in Figure 43.
From Figure 45 and 46, it can be found that the curve shape of motor speed in paper [295] and this report are the same, but the value is a little difference, that’s because in paper [295], the simulation environment is based on Simulink, the algorithm, solver, and the stepper time in the Simulink is different from the MATLAB which is used for the simulation in this report. Also, the motor speed is depending on the rotor resistance, inertial and friction of motor. For different parameters, the curve will be different.

The motor speed signal presents, however, strong oscillations in permanent regime, as shown in Figure 45, since torque ripple is large.
In equation (13), the term $i \cdot \omega \cdot dL/d\theta$ is the Back EMF induced voltage, which will be high for higher speeds. Using the linear inductance profile the minimum Back EMF value will be zero since $dL/d\theta = 0$, as shown in fig. 33. However, when the rotor position is in the zone where the inductance increases, the FEM voltage appears. When the Back EMF surpasses voltage V, phase current starts decreasing until the turn off angle is reached, as shown in Figure 47. The sharp switching effects present in the voltage energizing strategy clearly introduce harmonics in the torque signal, by phase current signal, that increase the motor speed ripple. Since this energized strategy is usually applied only when the motor reaches high speed values, the mechanical system will attenuate these harmonics from the motor speed signal.

Figure 48-49 shows a set of simulation results using $\theta_{on}=0^\circ$, $\theta_{off}=30^\circ$, and with the motor functioning with load applied.

- Figure 39 shows the simulation result of motor speed with load;
- Figure 40 shows the simulation result of one phase FEM with load;
From Figure 48 and 49, it can be seen clearly, once the motor with the load, the speed and the back EMF significant falling.

Dynamic behavior of the SRM is illustrated in a case where the hysteresis current controller is employed. These results, shown in Figure 50-55, have been achieved for $\theta_{on}=0^\circ$, $\theta_{off}=30^\circ$, and a current reference of $I_{ref}=8A$, with the motor functioning without load.

- Figure 50 shows the simulation result of one phase current with current control;
- Figure 51 shows the simulation result of one phase current in paper [295];
- Figure 52 shows the simulation result of one phase torque with current control;
- Figure 53 shows the simulation result of one phase torque in paper [295];
- Figure 54 shows the simulation result of motor speed with current control;
- Figure 55 shows the simulation result of motor speed in paper [295].
From Figure 50 and 51, it can be found that the curve shape of one phase current in paper [295] and this report are the same, but the control result in paper [295] is better than this report. That’s because in paper [295], the component of relay can be directed used based on the Simulink environment, in this paper, the solver and the stepper time is different, so the result will be different.

Figure 50 shows the influence of the hysteresis current control on the shape of phase current. One notices in this figure by zone 1 that the hysteresis band does not remain constant. During zone 1, the phase inductance remains constant and with its minimum value.
From Figure 52 and 53, it can be found that the curve shape of one phase torque in paper [295] and this report are the same, but the control result in paper [295] is better than this report. The reason is the same as the one phase current.

One can also observe in Figure 52 the current control influence on the phase torque.
Despite the result of current control in paper [295] is better than this report, the mean value of the phase current is same (equal to the reference current), so the motor speed in both paper [295] and this paper are almost the same, it can been seen in Figure 54 and 55.

The speed controller generates the reference current $i_{ref}$ for each motor phase, the simulation results for the speed control are shown in Figure 56 and 57.
The speed controller gains $K_p=0.568$ and $K_i=12$.

In Figure 56, the reference speed is set to 60 rad/s and Figure 57 shows the variable speed control result which the speed changes from 60 rad/s to 50 rad/s and then increases to 80 rad/s.

The simulation results prove that the controller is able to track the reference speed closely.

The response of the drive is good. The SRM reaches its reference speed of in 0.05s. The speed presents a small disturbance that is fast re-established by the controller.
Chapter 4

4. Conclusion

The goal of this report is to introduce the basic principles of switched reluctance motor, main motor and converter topologies, and mathematical approach.

Also this report has described and discussed in detail how from MATLAB one can achieve the simulation environment for SRM.

Torque or force production in a reluctance motor is developed from the variation of the stored magnetic energy as a function of the rotor position. Torque production, interval control and switching angles have been described.

From the simulation results, it can be seen that the switching angle has a significant impact to the SRM output (torque, speed, phase current and back EMF etc.) The current control and speed control works well, but it only works with the low motor speed.

By comparing the simulation results based on different simulation environment, it can be seen that the MATLAB environment and Simulink environment will significant impact the simulation results. The reason can be detailed studies for the future.

For the future studies, how to control this motor more precise can be considered.
References


Simulation of Switched Reluctance Motor and Control Based on MATLAB Environment


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Appendix A

Parameters of SRM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor poles</td>
<td>6</td>
</tr>
<tr>
<td>Stator poles</td>
<td>4</td>
</tr>
<tr>
<td>Phases</td>
<td>3</td>
</tr>
<tr>
<td>Input voltage</td>
<td>150V</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>1.3Ω</td>
</tr>
<tr>
<td>Inertial</td>
<td>0.0013Kg.m²</td>
</tr>
<tr>
<td>Friction</td>
<td>0.0183N.m.s</td>
</tr>
<tr>
<td>Inductance (maximum)</td>
<td>60mH</td>
</tr>
<tr>
<td>Inductance (minimum)</td>
<td>8mH</td>
</tr>
<tr>
<td>Turn-on angle</td>
<td>0°</td>
</tr>
<tr>
<td>Turn-off angle</td>
<td>30°</td>
</tr>
<tr>
<td>Commutation angle</td>
<td>60°</td>
</tr>
</tbody>
</table>
Appendix B

MATLAB Code

clc;
clear all;
close all;

%%% SRM model parameters %%%
NS=6;
NR=4;
p=3;
V=150;
TL=0;
W=0.0;
WLOAD=0.0;
ts=0.000065;
R=1.30;
J=0.0013;
F=0.0183;
DELTAI=0.2;
DELTAVMIN=0;
DELTAVMAX=150;
LMIN=8e-3;
LMAX=60e-3;
BETAS=30*(pi/180);
BETAR=30*(pi/180);
TETAS=(2*pi)*((1/NR)-(1/NS));
TETAX=(pi/NR)-((BETAR+BETAS)/2);
TETAY=(pi/NR)-((BETAR-BETAS)/2);
TETAZ=(BETAR-BETAS)/2;
TETAXY=(TETAY+TETAZ+TETAS);
TETAON=0.1*(pi/180);
TETAOFF=38*(pi/180);
TETAQ=60*(pi/180);
TETAIN=20.1*(pi/180);
G=(inv([TETAX 1;TETAY 1]))*[LMIN;LMAX];
AUP=G(1);
BUP=G(2);
H=(inv([TETAY+TETAZ 1;TETAXY 1]))*[LMAX;LMIN];
ADOWN=H(1);
BDOWN=H(2);
DL=AUP;

%%% Initializing motor parameters %%%
flux1=0;
flux2=0;
flux3=0;
Vp1=0;
Vp2=0;
Vp3=0;
I1=0;
I2=0;
I3=0;
theta_rem1(1)=0;
theta_rem2(1)=0;
theta_rem3(1)=0;
L1(1)=0;
L2(1)=0;
L3(1)=0;
Vp1(1)=0;
Vp2(1)=0;
Vp3(1)=0;
I1(1)=0;
I2(1)=0;
I3(1)=0;
flux1(1)=0;
flux2(1)=0;
flux3(1)=0;
T1(1)=0;
T2(1)=0;
T3(1)=0;
DL1(1)=0;
DL2(1)=0;
DL3(1)=0;
FEM1(1)=0;
FEM2(1)=0;
FEM3(1)=0;
FEM1LOAD(1)=0;
FEM2LOAD(1)=0;
FEM3LOAD(1)=0;
W(1)=0;
WLOAD(1)=0;
I1_pre=0;
Va1_pre=0;
theta_rem1(2)=0;
theta_rem2(2)=0;
theta_rem3(2)=0;
L1(2)=0;
L2(2)=0;
L3(2)=0;
Vp1(2)=0;
Vp2(2)=0;
Vp3(2)=0;
I1(2)=0;
I2(2)=0;
I3(2)=0;
flux1(2)=0;
flux2(2)=0;
flux3(2)=0;
T1(2)=0;
T2(2)=0;
T3(2)=0;
DL1(2)=0;
DL2(2)=0;
DL3(2)=0;
FEM1(2)=0;
FEM2(2)=0;
FEM3(2)=0;
FEM1LOAD(2)=0;
FEM2LOAD(2)=0;
FEM3LOAD(2)=0;
W(2)=0;
WLOAD(2)=0;
Iref(1)=0;
Iref_integral(1)=0;
tsim=0.5;
t=zeros(1,7000);

%%%%% Creating a vector for theta %%%%%
theta=0:pi/314.6:pi/2;

%%%%% Starting the euler method %%%%%
for i=2:tsim/ts

%%%%% Set Initial speed and PI gain parameters %%%%%
W_ref=60;
speed_p=0.568;
speed_i=12;

%%%%% Setting variable speed %%%%%
if i<(0.2/ts)
   W_ref=60;
elseif i<(0.35/ts)
   W_ref=50;
elseif i<(0.5/ts)
   W_ref=80;
end

%%%%% Speed control %%%%%
\text{diff}=(W_{\text{ref}}-W(i));
Iref\_integral(i)=Iref\_integral(i-1)+\text{diff}*\text{speed}_i*ts;
Iref(i)=Iref\_integral(i)+\text{diff}*\text{speed}_p;

%%%%% Angle process
theta\_rem1(i)=\text{rem}(\theta(i),\pi/2);
theta\_rem2(i)=\text{rem}(\theta(i)+\pi/6,\pi/2);
theta\_rem3(i)=\text{rem}(\theta(i)+\pi/3,\pi/2);

%%%%% Inductance calculation %%%%%
if ((0<=\theta\_rem1(i))&&(\theta\_rem1(i)<=\text{TETAX}))
   \text{L1}(i)=\text{LMIN};

end
end;
if ( (TETAX<theta_rem1(i)) && (theta_rem1(i)<=TETAY))
  L1(i)=(AUP*theta_rem1(i)+BUP);
end;
if ((TETAY<theta_rem1(i)) && (theta_rem1(i)<=TETAXY))
  L1(i)=(ADOWN*theta_rem1(i)+BDOWN);
end;
if ((theta_rem1(i))>TETAXY)
  L1(i)=LMIN;
end;

if ((0<=theta_rem2(i)) && (theta_rem2(i)<=TETAX))
  L2(i)=LMIN;
end;
if ( (TETAX<theta_rem2(i)) && (theta_rem2(i)<=TETAY))
  L2(i)=(AUP*theta_rem2(i)+BUP);
end;
if ((TETAY<theta_rem2(i)) && (theta_rem2(i)<=TETAXY))
  L2(i)=(ADOWN*theta_rem2(i)+BDOWN);
end;
if ((theta_rem2(i))>TETAXY)
  L2(i)=LMIN;
end;

if ((0<=theta_rem3(i)) && (theta_rem3(i)<=TETAX))
  L3(i)=LMIN;
end;
if ( (TETAX<theta_rem3(i)) && (theta_rem3(i)<=TETAY))
  L3(i)=(AUP*theta_rem3(i)+BUP);
end;
if ((TETAY<theta_rem3(i)) && (theta_rem3(i)<=TETAXY))
  L3(i)=(ADOWN*theta_rem3(i)+BDOWN);
end;
if ((theta_rem3(i))>TETAXY)
  L3(i)=LMIN;
end;

%%%%%% Voltage source %%%%%
if ((TETAON<=theta_rem1(i)) && (theta_rem1(i)<TETAOFF))
  Vp1(i)=V;

%%%%%% Current control %%%%%
I1(i)=0;
if ((I1(i-1)<I1(i)) && (I1(i-1) < (Iref(i)+DELTAI)))
  Vp1(i)=V;
end;
if ((I1(i-1)<I1(i)) && (I1(i-1) >= (Iref(i)+DELTAI)))
  Vp1(i)=-V;
end;
if ((I1(i-1)>=I1(i)) && (I1(i-1) >= (Iref(i)-DELTAI)))
  Vp1(i)=-V;

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end;
if ((I1(i-1)>I1(i)) && (I1(i-1) < (Iref(i)-DELTAI)))
    Vp1(i)=V;
end;

end;
if ((TETAOFF<theta_rem1(i))&&(theta_rem1(i)<=TETAQ))
    Vp1(i)=-V;
end;
if (theta_rem1(i)>TETAQ)
    Vp1(i)=0;
end;
if (0<=theta_rem1(i))&&(theta_rem1(i)<TETAON))
    Vp1(i)=0;
end;

if (theta_rem2(i)<TETAQ)
    Vp2(i)=V;

end;
if (theta_rem2(i)>TETAQ)
    Vp2(i)=0;
end;
if (0<=theta_rem2(i))&&(theta_rem2(i)<TETAON))
    Vp2(i)=0;
end;

if (I2(i-1)<I2(i)) && (I2(i-1) < (Iref(i)+DELTAI))
    Vp2(i)=V;
end;
if ((I2(i-1)<I2(i)) && (I2(i-1) >= (Iref(i)+DELTAI)))
    Vp2(i)=-V;
end;
if (I2(i-1)>I2(i)) && (I2(i-1) < (Iref(i)-DELTAI))
    Vp2(i)=V;
end;
if ((I2(i-1)>I2(i)) && (I2(i-1) >= (Iref(i)-DELTAI)))
    Vp2(i)=-V;
end;
if ((I2(i-1)>I2(i)) && (I2(i-1) < (Iref(i)-DELTAI)))
    Vp2(i)=V;
end;

end;
if ((TETAOFF<theta_rem2(i))&&(theta_rem2(i)<=TETAQ))
    Vp2(i)=-V;
end;
if (theta_rem2(i)>TETAQ)
    Vp2(i)=0;
end;
if (0<=theta_rem2(i))&&(theta_rem2(i)<TETAON))
    Vp2(i)=0;
end;

if ((TETAON<=theta_rem3(i))&&(theta_rem3(i)<=TETAOFF))
    Vp3(i)=V;
end;
I3(i)=0;
if ((I3(i-1)>I3(i)) && (I3(i-1) < (Iref(i)-DELTAI)))
    Vp1(i)=V;
end;
if ((I3(i-1)<I3(i)) && (I3(i-1) >= (Iref(i)+DELTAI)))
    Vp3(i)=-V;
end;
if ((I3(i-1)>=I3(i)) && (I3(i-1) >= (Iref(i)-DELTAI)))
    Vp3(i)=-V;
end;
if ((I3(i-1)>I3(i)) && (I3(i-1) < (Iref(i)-DELTAI)))
    Vp3(i)=V;
end;
end;
if ((TETAOFF<theta_rem3(i))&&(theta_rem3(i)<=TETAQ))
    Vp3(i)=-V;
end;
if (theta_rem3(i)>TETAQ)
    Vp3(i)=0;
end;
if ((0<=theta_rem3(i))&&(theta_rem3(i)<TETAON))
    Vp3(i)=0;
end;

%%% Current calculation %%%
if ((0<=theta_rem1(i))&&(theta_rem1(i)<=TETAX))
    I1(i)=flux1(i)/LMIN;
end;
if ((TETAX<theta_rem1(i))&&(theta_rem1(i)<=TETAY))
    I1(i)=flux1(i)/((AUP*theta_rem1(i))+BUP);
end;
if ((TETAY<theta_rem1(i))&&(theta_rem1(i)<=TETAXY))
    I1(i)=flux1(i)/((ADOWN*theta_rem1(i))+BDOWN);
end;
if (theta_rem1(i)>TETAXY)
    I1(i)=flux1(i)/LMIN;
end;
if ((0<=theta_rem2(i))&&(theta_rem2(i)<=TETAX))
    I2(i)=flux2(i)/LMIN;
end;
if ((TETAX<theta_rem2(i))&&(theta_rem2(i)<=TETAY))
    I2(i)=flux2(i)/((AUP*theta_rem2(i))+BUP);
end;
if ((TETAY<theta_rem2(i))&&(theta_rem2(i)<=TETAXY))
    I2(i)=flux2(i)/((ADOWN*theta_rem2(i))+BDOWN);
end;
if (theta_rem2(i)>TETAXY)
    I2(i)=flux2(i)/LMIN;
end;
if ((0<=theta_rem3(i))&&(theta_rem3(i)<=TETAX))
    I3(i)=flux3(i)/LMIN;
end;
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```matlab
if ((TETAX<theta_rem3(i))&&(theta_rem3(i)<=TETAY))
    I3(i)=flux3(i)/((AUP*theta_rem3(i))+BUP);
end;
if ((TETAY<theta_rem3(i))&&(theta_rem3(i)<=TETAXY))
    I3(i)=flux3(i)/((ADOWN*theta_rem3(i))+BDOWN);
end;
if (theta_rem3(i)>TETAXY)
    I3(i)=flux3(i)/LMIN;
end;
while I1(i)<0
    I1(i)=0;
end;
while I2(i)<0
    I2(i)=0;
end;
while I3(i)<0
    I3(i)=0;
end;

%%%%%% compute torque %%%%%%%%%
if ((0<=theta_rem1(i))&&(theta_rem1(i)<=TETAX))
    T1(i)=0;
end;
if ((TETAX<theta_rem1(i))&&(theta_rem1(i)<=TETAY))
    T1(i)=0.5*(DL)*(I1(i)*I1(i));
end;
if ((TETAY<theta_rem1(i))&&(theta_rem1(i)<=TETAXY))
    T1(i)=-0.5*(DL)*(I1(i)*I1(i));
end;
if (theta_rem1(i)>TETAXY)
    T1(i)=0;
end;
while T1(i)<0
    T1(i)=0;
end;
if ((0<=theta_rem2(i))&&(theta_rem2(i)<=TETAX))
    T2(i)=0;
end;
if ((TETAX<theta_rem2(i))&&(theta_rem2(i)<=TETAY))
    T2(i)=0.5*(DL)*(I2(i)*I2(i));
end;
if ((TETAY<theta_rem2(i))&&(theta_rem2(i)<=TETAXY))
    T2(i)=-0.5*(DL)*(I2(i)*I2(i));
end;
if (theta_rem2(i)>TETAXY)
    T2(i)=0;
end;
while T2(i)<0
    T2(i)=0;
end;
```
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end;

if ((0<=theta_rem3(i))&&(theta_rem3(i)<=TETAX))
    T3(i)=0;
end;
if ((TETAX<theta_rem3(i))&&(theta_rem3(i)<=TETAY))
    T3(i)=-0.5*(DL)*(I3(i)*I3(i));
end;
if ((TETAY<theta_rem3(i))&&(theta_rem3(i)<=TETAXY))
    T3(i)=0.5*(DL)*(I3(i)*I3(i));
end;
if (theta_rem3(i)>TETAXY)
    T3(i)=0;
end;
while T3(i)<0
    T3(i)=0;
end;
T(i)=T1(i)+T2(i)+T3(i);

%% Flux calculation
flux1(i+1)=flux1(i)+(Vp1(i)-(R*I1(i)))*ts;
flux2(i+1)=flux2(i)+(Vp2(i)-(R*I2(i)))*ts;
flux3(i+1)=flux3(i)+(Vp3(i)-(R*I3(i)))*ts;

%% FEM calculation
if ((0<=theta_rem1(i))&&(theta_rem1(i)<=TETAX))
    DL1(i)=0;
end;
if ((TETAX<theta_rem1(i))&&(theta_rem1(i)<=TETAY))
    DL1(i)=DL;
end;
if ((TETAY<theta_rem1(i))&&(theta_rem1(i)<=TETAXY))
    DL1(i)=-DL;
end;
if (theta_rem1(i)>TETAXY)
    DL1(i)=0;
end;
if ((0<=theta_rem2(i))&&(theta_rem2(i)<=TETAX))
    DL2(i)=0;
end;
if ((TETAX<theta_rem2(i))&&(theta_rem2(i)<=TETAY))
    DL2(i)=DL;
end;
if ((TETAY<theta_rem2(i))&&(theta_rem2(i)<=TETAXY))
    DL2(i)=-DL;
end;
if (theta_rem2(i)>TETAXY)
    DL2(i)=0;
end;
if ((0<=theta_rem3(i))&&(theta_rem3(i)<=TETAX))
    DL3(i)=0;
end;
if ((TETAX<theta_rem3(i))&&(theta_rem3(i)<=TETAY))
    DL3(i)=DL;
end;
if ((TETAY<theta_rem3(i))&&(theta_rem3(i)<=TETAXY))
    DL3(i)=-DL;
end;
if (theta_rem3(i)>TETAXY)
    DL3(i)=0;
end;
FEM1LOAD(i)=I1(i)*WLOAD(i)*DL1(i);
FEM2LOAD(i)=I2(i)*WLOAD(i)*DL2(i);
FEM3LOAD(i)=I2(i)*WLOAD(i)*DL3(i);
FEM1(i)=I1(i)*W(i)*DL1(i);
FEM2(i)=I2(i)*W(i)*DL2(i);
FEM3(i)=I2(i)*W(i)*DL3(i);

%%% Disturbance applied %%%
t(i+1)=t(i)+ts;
if (t(i+1)>tsim/4)&&(t(i+1)<tsim/3.9);
    TL=2;
end;

%%% Speed calculation %%%
WLOAD(i+1)=ts/J*(T(i)-TL-F*WLOAD(i))+WLOAD(i);
W(i+1)=ts/J*(T(i)-F*W(i))+W(i);
theta(i+1)=theta(i)+(pi/314.6);
end;

%%% Plotting figures %%%
figure(1)
plot (t(1:end-1),L1,t(1:end-1),L2,t(1:end-1),L3)
figure(2)
plot (t(1:end-1),Vp1)
figure(3)
plot (t,W)