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Intitulé du sujet

Contribution to SRM design for industrial application

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بسم الله الرحمن الرحيم

﴿اقْرَأْ بِاسْمِ رَبِّكَ الَّذِي خَلَقَ ۝ خَلَقَ الْإِنْسَانَ مِنْ عَلَقٍ ۝ اقْرَأْ وَرَبُّكَ الْأَكْرَمُ
۝ الَّذِي عَلَّمَ بِالْقَلَمِ ۝ عَلَّمَ الْإِنْسَانَ مَا لَمْ يَعْلَمْ﴾

[سورة العلق :1-5]

﴿لَقَدْ أَرْسَلْنَا رُسُلَنَا بِالْبَيِّنَاتِ وَأَنزَلْنَا مَعَهُمُ الْكِتَابَ وَالْمِيزَانَ لِيَقُومَ النَّاسُ بِالْقِسْطِ ۖ
وَأَنزَلْنَا الْحَدِيدَ فِيهِ بَأْسٌ شَدِيدٌ وَمَنَافِعُ لِلنَّاسِ وَلِيَعْلَمَ اللَّهُ مَن يَنصُرُهُ وَرُسُلَهُ
بِالْغَيْبِ ۚ إِنَّ اللَّهَ قَوِيٌّ عَزِيزٌ﴾

[سورة الحديد: 25]

﴿سنريهم آياتنا في الآفاق وفي أنفسهم حتى يتبين لهم أنه الحق أو لم يكف بربك
أنه على كل شيء شهيد﴾

[سورة فصلت: 53]

الاهداء

الحمد الله رب العالمين بعد تعب ومشقة دامت 5 سنوات في سبيل الحلم والعلم حملت في طياتها امنيات الليالي وأصبح عنائي اليوم للعين قرة، ها انا اليوم أقف على عتبة تخرجي اقطف ثمار تعبي وارفع قبعتي بكل فخر فاللهم لك الحمد قبل ان ترضى ولك الحمد إذا رضيت ولك الحمد بعد الرضا، لأنك وفقتني على اتمام هذا النجاح وتحقيق حلمي

وبكل حب اهدي ثمرة نجاحي وتخرجي

الى التي زينت اسمي بأجمل الالقاب، من دعمتني بلا حدود واعطتني بلا مقابل الى من علمتني ان الدنيا كفاح وسلاحها العلم والمعرفة، داعمتي الاولة في مسيرتي وسندي وقوتي وملاذي بعد الله فخري واعتزازي

(والدتي)

الى من ساندني بكل حب عند ضعفي وازاح عن طريقي المتاعب ممهدا لي الطريق زرع الثقة والاصرار بداخلي
الى من شد الله به عضدي فكان خير معين

(اخي خليل)

الى جميع من امدوني بالقوة والتوجيه وامن بي ودعمني في الاوقات الصعبة لأصل الى ما انا عليه الان، وفقهم الله

HAMDI ACHOUAK

الاهداء

الحمد الله رب العالمين بعد تعب ومشقة دامت 5 سنوات في سبيل الحلم والعلم حملت في طياتها امنيات الليالي وأصبح عنائي اليوم للعين قرة، ها انا اليوم أقف على عتبة تخرجي اقطف ثمار تعبي وارفع قبعتي بكل فخر فاللهم لك الحمد قبل ان ترضى ولك الحمد إذا رضيت ولك الحمد بعد الرضا، لأنك وفقتني على اتمام هذا النجاح وتحقيق حلمي

وبكل حب اهدي ثمرة نجاحي وتخرجي

الى روح غالية فارقتني وانا لا زلت متعلقة بها الى روح انتزعت من روحي الى روح فجعتني برحيلها الى بسمة وضحكة لا تغيب عن البال بقيت مخلد في قلبي حتى نلتقي رحمك الله يا قطعة مني

(والدي و والدتي)

الى ملائكة رزقني الله بهم لأعرف من خلالهم طعم الحياة الجميلة، تلك الملائكة التي غيروا مفاهيم الحب والصداقة والسند في حياتي

(اخوتي نسرين، امينة، مصطفى)

GAIDI LOUIZA

ملخص

الغرض من هذه الدراسة هو تقليل تموج عزم الدوران في التطبيقات خارج الشبكة باستخدام محرك التردد المحول م م م. نبضات عزم دوران العمود نتيجة لعملية المحرك المتوقفة وغير الخطية للغاية لإنتاج عزم الدوران. تم إخضاع أربعة نماذج متميزة من م م م قطب 6/8 للتحليل البارا متري وتعديل القطب. لزيادة الدقة، تم استخدام تحليل العناصر المحدودة ثلاثية الأبعاد. يوفر النموذج المحسن متوسط عزم الدوران والتخفيف القوي من تموج عزم الدوران.

الكلمات الدالّة: محرّك متغير المُمانعة، معادلات ماكسويل، العزم، التحسين، الاهتزاز، طريقة العناصر المحدودة.

Abstract

The purpose of this study is to reduce torque ripple in off-grid applications using a switched reluctance motor (SRM). Shaft torque pulses as a result of the motor's discontinuous and extremely nonlinear process for producing torque. Four distinct 8/6 pole SRM models were subjected to parametric analysis and pole modification. For increased precision, 3D finite element analysis was employed. The optimized model provides improved average torque and strong torque ripple mitigation.

Key words: Switched Reluctance Machine, Maxwell Equations, torque, optimization, vibration, Finite Element Method.

Résumé

Le but de cette étude est de réduire l’ondulation de couple dans les applications hors réseau en utilisant un moteur à réluctance commuté (). Impulsions de couple d’arbre résultant du processus discontinu et extrêmement non linéaire du moteur pour produire le couple. Quatre modèles SRM distincts de 8/6 pôles ont été soumis à une analyse paramétrique et à une modification des pôles. Pour une précision accrue, l’analyse par éléments finis 3D a été utilisée. Le modèle optimisé offre un couple moyen amélioré et une forte atténuation de l’ondulation du couple.

Mots clés : Machine a reluctance variable, couple, optimisation, vibration, méthode des éléments finis, équations de maxwell.

Acknowledge men

Praise be to ALLAH, his Majesty for his uncountable blessings, and best prayers and peace be unto his best messenger Muhammad, his pure descendant, and his family and his noble companions.

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Notations and symbols

SRMs	Switched reluctance motors.
FEM	Finite element method.
FEA	Finite element analysis.
DC	Direct current.
AC	Alternating current.
HVAC	Heating, ventilation, and air conditioning.
NPSH	Net positive suction head
CNC	Computer numerical control.
$\mathbf{N_r}$	Rotor pole number.
$\mathbf{N_s}$	Stator pole number.
μ_o	Permeability of free space.
μ_r	Relative permeability.
μ	Total permeability.
σ	The electric conductivity [S/m].
$\vec{E}$	Electric field intensity (Unit: V/m).
ε	Permittivity.
ε_0	Permittivity of free space.
ε_r	Relative permittivity.
$\vec{J}$	Electric current density (A/m^2).
μ_o	Permeability magnetic of free space.

$\vec{\boldsymbol{B}}$	Magnetic flux density (Unit: Tesla=Vs/m2).
$\boldsymbol{\rho}$	Electric charge density (Unit: C/m^3).
$\vec{\boldsymbol{D}}$	Electric flux density/displacement field (Unit: C/m^2).
$\boldsymbol{\varepsilon_r}$	Rotor factor embrace.
$\boldsymbol{\varepsilon_s}$	Stator factor embrace.
$\vec{\mathbf{A}}$	Magnetic field lines
$\boldsymbol{\varepsilon_r}$	Rotor factor embrace.
$\boldsymbol{\varepsilon_s}$	Stator factor embrace.
Ph	Hydraulic power in watts (W).
Q	Flow rate in cubic meters per second (m^3/s).
H	Discharge head in meters (m).
P	Fluid density in kilograms per cubic meter (kg/m^3).
g	The acceleration due to gravity (m/s2).
hp	Pump efficiency (%).
Pm	Motor power in watts (W).

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II Chapter two: Electromagnetic equations and FEM analysis

III Chapter three: Optimization and industrial applications

General introduction

Switched Reluctance Motors (SRMs) is very important in water pumping, because of their high efficiency, reliability, and low maintenance requirements. However, SRMs are frequently affected from high torque ripple and vibrations, which can lead to reduced system performance, increased wear and tear, and decreased lifespan.

In Chapter one, we delve into the foundational aspects of SRMs. These motors operate on the principle of magnetic reluctance, leveraging the interaction between the stator windings and a solid, salient-pole rotor made from magnetic material. Unlike traditional motors, SRMs do not incorporate magnets in the rotor, relying instead on the magnetic reluctance force generated to achieve rotational motion.

Chapter two explores the theoretical framework underpinning SRMs, emphasizing electromagnetism and Maxwell's equations. Our investigation underscores the pivotal role of electromagnetism in understanding how electric and magnetic fields interact to propel SRM functionality. Maxwell's equations, foundational to electromagnetism, provide essential tools for modeling and optimizing SRM designs, ensuring efficient performance across various operational conditions.

In Chapter three, we pivot towards practical implementation by optimizing SRM performance using Ansys software. Here, we analyze how different rotor and stator geometries impact torque characteristics and operational efficiency. By maintaining a constant ampere-turn configuration and varying key design parameters such as pole configuration (8/6), we aim to enhance SRM performance metrics like torque ripple and overall motor efficiency.

Through our study, we aim to deepen the understanding of SRMs, bridging theoretical insights with practical applications. By integrating theoretical foundations with optimization techniques, we endeavor to advance the development of SRMs for diverse industrial applications, ensuring improved reliability and performance in electric vehicles, industrial pumps, and beyond [1], [2], [3], [4], [5], [6], [7], [8], [9].

I Chapter one

Generalities of SRM

I.1 Introduction

Switched Reluctance Motors (SRMs) are a type of electric motor that operates based on the principle of variable reluctance, motor that operates primarily based totally at the precept of magnetic reluctance ,SRMs are known for their simplicity, robustness, and efficiency, SRMs operate on the principle of reluctance torque, which is generated by the tendency of the rotor to align with the magnetic field created by the stator windings, It is an electric powered motor that has wound area coils with inside the stator, at the same time as the rotor is fabricated from a stable salient-pole rotor fabricated from smooth magnetic material. Unlike traditional motors, SRMs nowadays no longer have magnets or coils inside the rotor, instead strength is added to the windings inside the stator, and the rotor`s magnetic reluctance creates a pressure that tries to align the rotor pole with the closest stator pole, Its essential disadvantage is torque ripple, which may be minimized with superior controller technology, this change is exploited to produce rotational motion, this motor type is particularly suitable for industrial applications that require high reliability and low maintenance, such as water pumping systems and electric vehicles [1],[2].

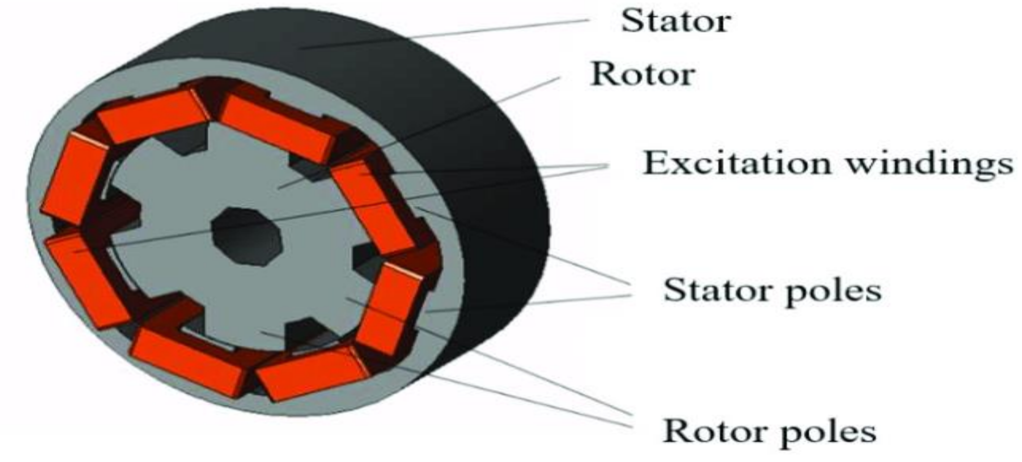


Figure I-1: design of SRM machine.

In this chapter, we will present a general study on SRM about its structure, Principle of operation,

In addition, types of SRM, Advantages and Disadvantages are described.

I.2 General on SRM

There are several types of switched reluctance machine (cylindrical, linear, Vernier big-toothed…). The typical example of this machine is the electromagnet used in relays, contactors, etc. it comes in many forms but still has a fixed part called core and moving part called armature. The core can take the form of a U, an E or of a cylinder and the armature can be flat, plunging or rotating. Figure I-2 gives examples of electromagnet structures [3].

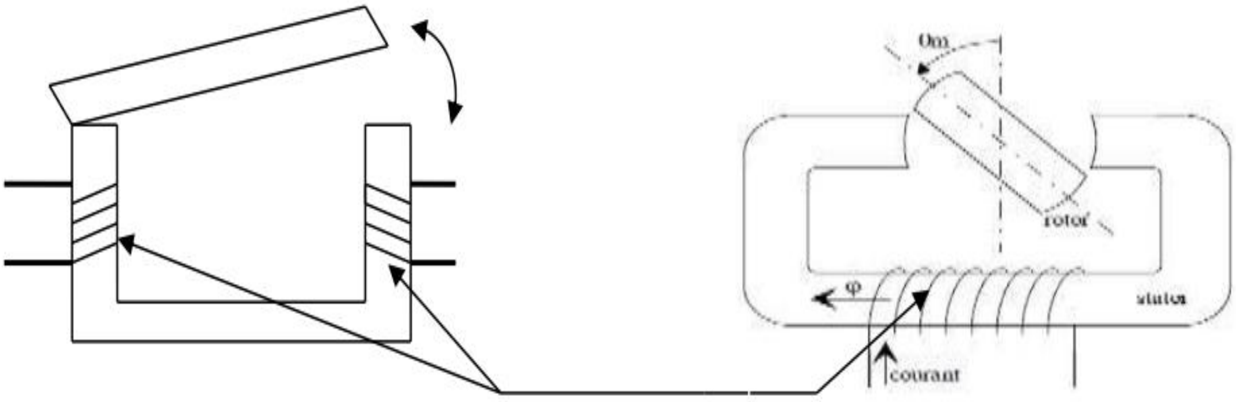


Figure I-2: Electromagnets, (a) U-core. frame with swivel valve (b) Rotating frame.

But engines also use the principle of variable reluctance. Figure 1-2 gives examples of oscillating motor (electric razor type) and stepper motor. For this last the sequential feeding of phases in the order A.B.C corresponds to a direction of counter-clockwise rotation and in the order A.C.B in a clockwise direction. The passage of the power supply from phase A to phase B causes an elementary rotation of a second turn of rotor called: elementary pitch [3].

I.3 Principle of operation

The rotor of the switched reluctance motor continuously seeks to align through the lowest reluctance lane in accordance with the principle of changing reluctance.

The circuit of power electronics switching can be used to create a rotating magnetic field. In this case, the air gap may be the primary determinant of the magnetic circuit's resistance. Thus, we can adjust the reluctance of this motor by altering the air gap between the rotor and stator. Reluctance in this context is defined as opposition to the magnetic flux. Reluctance in electrical circuits is the result of the magnetic circuit and resistance working together [1].

I.4 Types of SRM

Switched reluctance motors can be categorized using techniques such as linear and rotary SRM construction.

I.4.1 Linear

The linear SRM are known as servos in the market. Together with the rotor, it also has a single-step stator.

I.4.2 Rotary

The rotary SRM are available in two types like radial field as well as the axial field and radial field. Single stack and multi-stack axial field SRMs are the two categories into which they are divided. There are multiple rotors and stators in this rotating SRM [4].

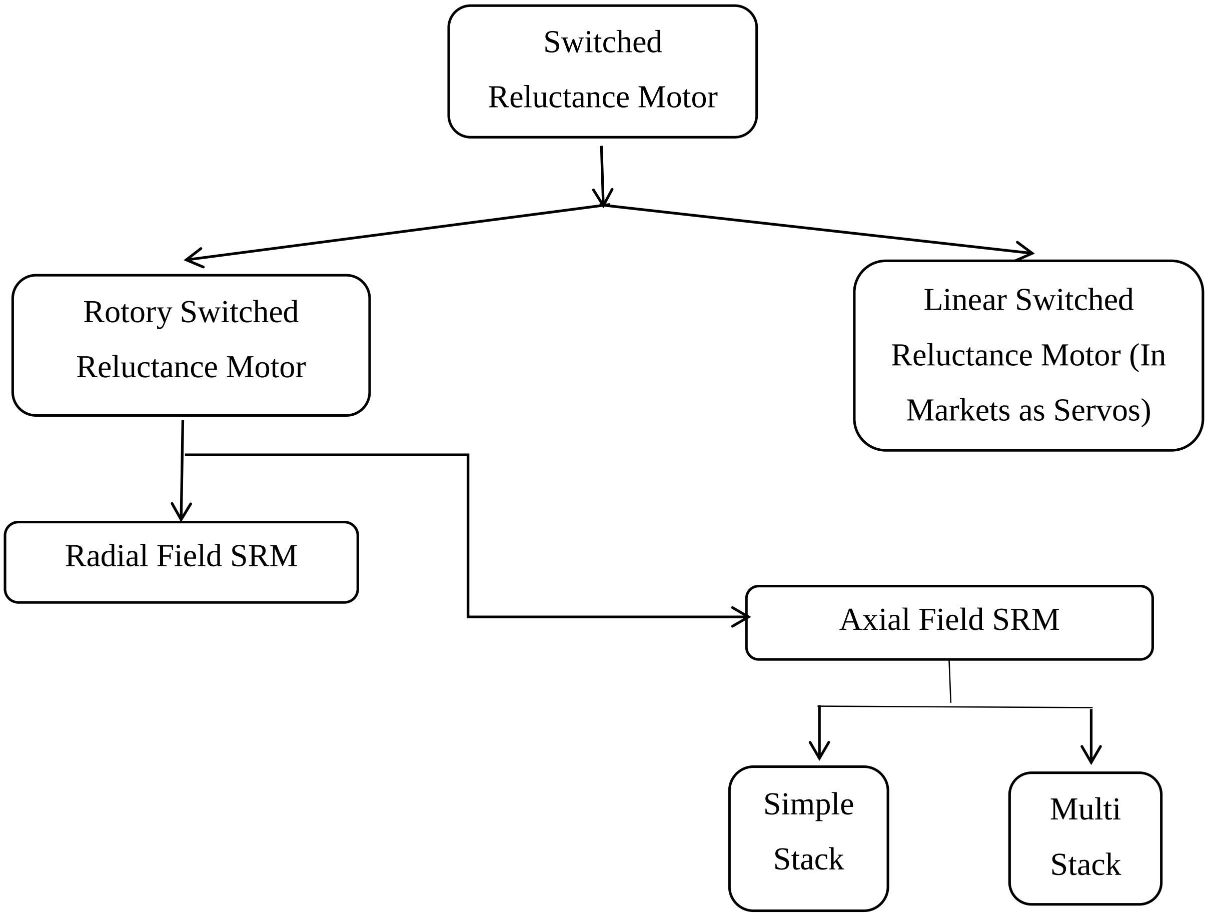


Figure I-3: Classification of switched reluctance motors.

I.5 Construction of SRM

The construction of a Switched Reluctance Motor (SRM) involves the following components:

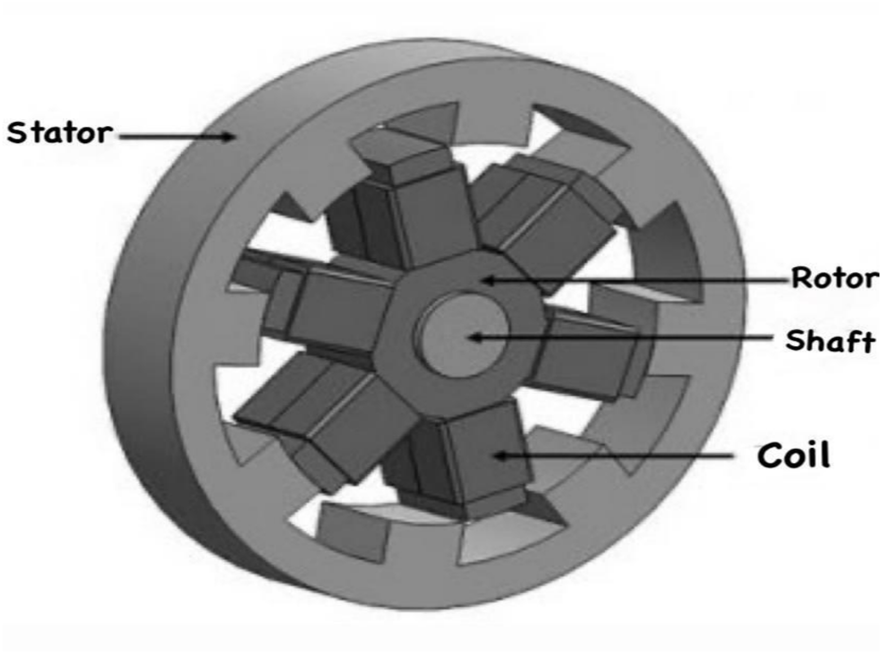


Figure I-4: Construction of SRM 8/6.

Stator: The motor's stator, which holds the windings, is its stationary component. Usually, the windings are arranged in a particular way to produce a magnetic field.

Rotor: Usually composed of laminated steel, the rotor is the motor's moving component and is composed of a soft magnetic substance. Salient poles are magnetic poles that protrude from the rotor.

Windings: The wire coils encircling the stator are known as windings. To produce a rotating magnetic field, the windings are connected to a power source and turned on and off in a predetermined order.

Electronic control system: To keep the windings rotating, the electronic control system must turn them on and off in the proper order. The rotor shaft angle is detected by the system using an electronic position sensor, and the stator windings are switched via solid-state electronics.

Sensor position: In order to turn the windings on and off at the appropriate times, it is necessary to ascertain the rotor shaft's angle.

The construction of an SRM is simpler than that of a traditional brushed DC motor, as it does not require a commutator or brushes. The electrical control system is more intricate, though, since it must time the winding switches exactly right in order to keep the rotation going [4].

I.6 Machine structure

The double-toothed switched reluctance machine is a field synchronous machine pulsed. The rotor and stator are both toothed, the rotor has no winding or permanent magnet while stator has winding around constituent teeth as well the machine poles, the magnetic circuits of the stator and rotor are built from a stacking of magnetic sheets to avoid losses by eddy current, the structure of an 8/6 SRM (eight stator tooth and six rotor tooth) is presented on the Figure below [5], [6].

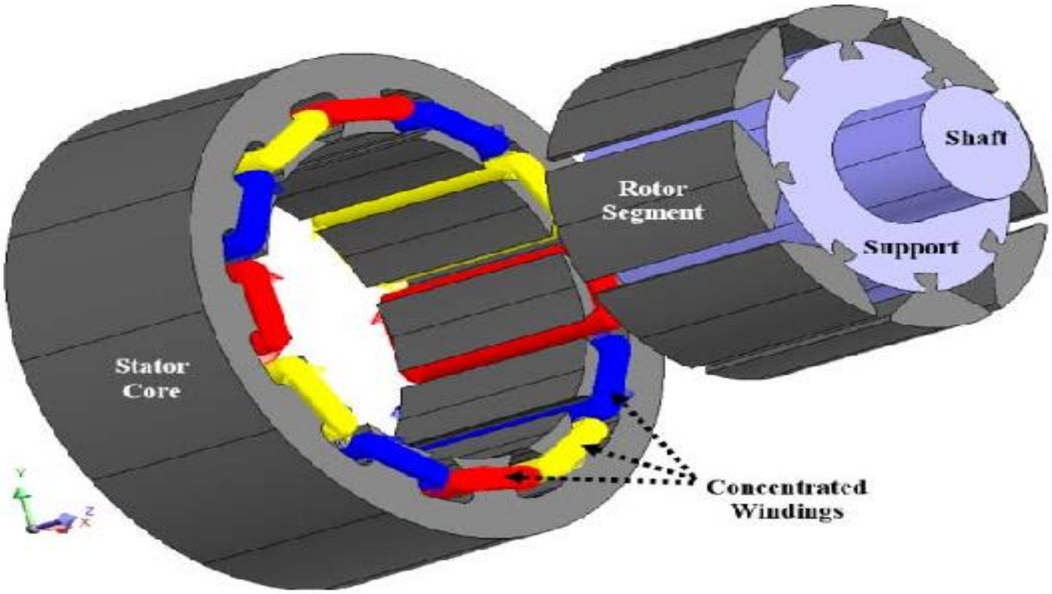


Figure I-5: Detailed 3D structure of a SRM 8/6.

I.7 SRM characteristics

The characteristics of the switched reluctance motor include the one that follows.

- This kind of reluctance motor is a 1-phase or 3-phase.

- This motor's speed control is easy to use.
- To achieve high speed, the triggering circuit can be modified.
- When used with an inverter, it runs on a DC power.
- Various speeds can be attained by adjusting the firing angle of any switching device.
- One phase's control is unrelated to the other two phases.
- The feedback diodes can be used to recover the energy that was not used when feeding the motor. This enhances effectiveness [7].

I.8 Applications of SRM

The simple motor structure and inexpensive power electronic requirement have made the SRM an attractive alternative to both AC and DC machines in adjustable-speed drives. Few of such applications are listed below [4], [8].

A. General purpose industrial drives.
B. Application-specific drives: compressors, fans, pumps, centrifuges.
C. Domestic drives: food processors, washing machines, vacuum cleaners.
D. Electric vehicle application.
E. Aircraft applications.
F. Servo-drive.

Figure I-6: Application of SRM.

I.9 Comparing 6/4 and 8/6

Switched Reluctance Motors (SRMs) are classified based on the number of stator and rotor poles they have. The first number represents the number of stator poles, while the second number represents the number of rotor poles.

- **6/4 Switched Reluctance Motor:** This motor has 4 stator poles and 6 rotor poles. The 6/4 SRM is a simple and robust motor that is often used in low-cost applications. It has a lower torque density compared to other SRM configurations, but it is easier to control and manufacture.
- **8/6 Switched Reluctance Motor:** This motor has 6 stator poles and 8 rotor poles. The 8/6 SRM has a higher torque density compared to the 6/4 SRM. It is more complex to control and manufacture, but it can provide better performance in terms of torque and speed [9].

I.9.I Implementation 6/4

Low-cost applications: Fans, pumps, and compressors are just a few examples of the low-cost devices that frequently use the 6/4 SRM, a sturdy and basic motor.

HVAC systems: Because of its affordable price and straightforward construction, the 6/4 SRM is utilized in HVAC (heating, ventilation, and air conditioning) systems.

Automotive uses: When a straightforward and dependable motor is needed for automotive applications, including gasoline and water pumps, the 6/4 SRM is employed.

Automation in industry: The 6/4 SRM is utilized in applications requiring a low-cost motor, including as material handling systems and conveyor belts.

I.9.II Implementation 8/6

High-performance applications: When a high torque density and speed are necessary, such as in electric cars, robotics, and aircraft, the 8/6 SRM is employed.

Applications for servos: The 8/6 SRM is employed in servo applications that require high torque and accurate control, like robotics and CNC machines.

Renewable energy systems: When a high torque density and efficiency are needed, the 8/6 SRM is employed in renewable energy systems like wind turbines and wave energy converters.

Electric cars: Because of the 8/6 SRM's excellent torque density and efficiency, it is utilized in electric vehicles.

In conclusion, low-cost applications, HVAC systems, automotive applications, and industrial automation are popular uses for the 6/4 SRM, whereas high-performance applications are common uses for the 8/6 SRM servo applications, renewable energy systems, and electric vehicles.

I.10 Advantages of SRM

High Efficiency: SRMs are regarded for his or her excessive efficiency, in particular at excessive speeds and loads [1], [10], [11].

Reliability: With no brushes or commentators, SRMs have fewer wear-inclined components than different kinds of cars.

Cost-Effective: SRMs may be much less steeply-priced to fabricate and preserve because of their easier design.

High Power-to-Weight Ratio: SRMs can supply an excessive power-to-weight ratio, making them appropriate for packages wherein length and weight are critical.

Operational Flexibility: SRMs can function in any quadrant of the torque-pace plane, making them appropriate for an extensive variety of packages.

I.11 Disadvantages of SRM

High Acoustic Noise: SRMs can produce excessive degrees of acoustic noise because of the magnetic forces appearing at the rotor [1], [10], [11].

Complex Control: SRMs require extra complicated manage algorithms than different kinds of cars, that may boom the fee and complexity of the pressure system.

Torque Ripple: SRMs can produce torque ripple, that may result in vibrations and noise.

Lower Dynamic Performance: SRMs could have decrease dynamic overall performance than different kinds of cars because of their exceedingly excessive inertia.

I.12 Conclusion

Switched Reluctance Motors (SRMs) are a more and more famous form of electric powered motor with numerous advantages. They are strong and reliable, with an easy layout that reduces production and protection costs. SRMs also are fee-powerful and durable, with a rotor that doesn't include any windings, magnets, or squirrel cages. This precise layout, primarily based totally at the precept of magnetic attraction, lets in for excessive torque-to-inertia ratio and excessive efficiency. However, there are a few hazards to SRMs. They can produce excessive stages of acoustic noise, which may be a sizeable trouble in positive packages. SRMs additionally require extra complicated manage algorithms than different varieties of automobiles, which could growth the fee and complexity of the pressure system. Additionally, SRMs can produce torque ripple, which could cause vibrations and noise. Despite those challenges, SRMs are broadly utilized in diverse packages, together with automotive, industrial, and business packages. They are especially appropriate for packages in which size, power-to-weight ratio, and reliability are critical Overall, SRMs provide a completely unique and feasible opportunity to standard electric powered automobiles in lots of packages.

II Chapter two
Electromagnetic Equations and FEM Analysis

II.1 Introduction

One of the main principles of contemporary physics is electromagnetism, which ties together the study of electric and magnetic fields and their interactions. The four basic equations known as Maxwell's equations, which neatly characterize the behavior of electric and magnetic fields and their relationships with electric charges and currents, are the foundation of this field of study.

This chapter delves into the complexities of Maxwell's equations and electromagnetic, examining its importance and potential uses in a range of scientific and technical fields. Since James Clerk Maxwell's groundbreaking work in the 19th century to the most recent developments, the study of electromagnetic has advanced steadily, deepening our understanding of the cosmos and spurring technological improvements.

Additionally, we investigate the Finite Element Method (FEM), a potent numerical method that is frequently applied to the solution of partial differential equations, such as Maxwell's equations. Engineers and scientists may precisely and efficiently model and analyze complicated electromagnetic phenomena using the FEM, which makes it possible to build and optimize electromagnetic devices and systems.

In order to shed light on the theoretical foundations and real-world application of electromagnetism, Maxwell's equations, and the Finite Element Method, this chapter attempts to provide a thorough overview of each of these topics. Readers can comprehend the fundamentals of electromagnetic theory and its significant influence on numerous scientific and technical domains by comprehending these ideas and techniques [12], [13], [14].

II.2 Definition of electromagnetism

The study of electric and magnetic fields and their interactions is known as electromagnetic, and it is a basic branch of physics. It is founded on the ideas of Maxwell's equations, which explain how currents and electric charges combine to create magnetic and electric fields. Nerve impulses are sent as electric signals or waves of electric potential in neural systems, where the electric and magnetic energy in the human body is vital. In order to describe the electric and magnetic fields around charged things traveling at non-relativistic speeds, Galilean electromagnetism offers a formal electromagnetic field theory that is consistent with Galilean invariance. By ignoring some coupling variables, this theory makes mathematical equations simpler and permits low-frequency approximations in electrical networks [15], [16], [17].

II.3 Maxwell’s equations

A collection of basic equations known as Maxwell's equations characterize the interaction between electric and magnetic fields in electromagnetism. They were first presented by James Clerk Maxwell in the 1800s and are crucial to comprehending how electromagnetic fields behave. There are four equations in the set that link the sources of magnetic and electric fields. These are Ampère's law with Maxwell's inclusion of the displacement current term, Faraday's law of electromagnetic induction, Gauss's law, and Gauss's law for magnetism. Maxwell completed the set of equations by including the displacement current term, which takes into account the time-varying electric field in a dielectric medium and permits the prediction of electromagnetic waves. Modern physics has developed on the basis of these equations [18], [19], [20], [21].

- **Maxwell-Gauss équation**

$$\vec{\nabla} \cdot \vec{D} = \rho \quad \text{or} \quad \vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \tag{II.1}$$

ρ = electric charge density (Unit: C/m^3).

$\vec{D}$ = electric flux density/displacement field (Unit: C/m^2).

- **Magnetic flux conservation équation**

$$\vec{\nabla} \cdot \vec{B} = 0 \tag{II.2}$$

$\vec{B}$ = magnetic flux density (Unit: Tesla=Vs/m2).

- **Maxwell-faraday équation**

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{II.3}$$

$\vec{B}$ = magnetic flux density (Unit: Tesla=Vs/m2).

$\vec{E}$ = electric field intensity (Unit: V/m).

- **Maxwell-Ampère équation**

$$\vec{\nabla} \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t} \qquad \text{Or} \qquad \vec{\nabla} \times B = \mu_\circ \vec{j} + \mu_0 \varepsilon_0 \frac{\partial \vec{\epsilon}}{\partial \mathrm{t}} \qquad (\text{II.4})$$

$\vec{j}$ = electric current density (A/m^2).

μ_o=permeability magnetic of free space.

where $\vec{\boldsymbol{H}}$ [A/m] is the magnetic field intensity, $\vec{\boldsymbol{B}}$ [T or w_b / m^2] is the magnetic flux density, $\vec{\boldsymbol{E}}$ [V/m] is the electric field intensity, $\vec{\boldsymbol{j}}$ [A/m^2] is the current density, t is the time, ∇· and ∇× are the divergence and curl operators respectively. Al- tentatively, these equations can be expressed in integral form and are summarized in table II.1.

Governing Laws	Differential Form	Integral Form
Gauss' Law	$\vec{\nabla} \cdot \vec{D} = \rho$	$\oiint_S \vec{D} \cdot d\vec{S} = \iiint_V \rho \, dV$
Gauss's law for magnetism	$\vec{\nabla} \cdot \vec{B} = 0$	$\oiint_S \vec{B} \cdot d\vec{S} = 0$
Ampere's Law	$\vec{\nabla} \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}$	$\oint_{\partial S} \vec{H} \cdot d\vec{L} = \iint_S \vec{j} \cdot d\vec{S} + \iint_S \frac{\partial \vec{D}}{\partial t} \cdot d\vec{S}$
Faraday's Law	$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$	$\oint_{\partial s} \vec{E} \cdot d\vec{L} = -\iint_s \frac{\partial \vec{B}}{\partial t} \cdot d\vec{s}$

Table II-1: Maxwell's Equations for Quasi-Static Fields.

The following constitutive laws define the material qualities related to the aforementioned Maxwell's equations:

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

$$\vec{D} = \varepsilon \, \vec{E}$$

$$\vec{D} = \varepsilon_0 \varepsilon_r \vec{E} \qquad (\text{II.5})$$

$\vec{D}$ = electric flux density/displacement field (Unit: C/m^2).

$\vec{E}$ = electric field intensity (Unit: V/m).

ε = Permittivity.

ε_0=permittivity of free space.

ε_r= Relative permittivity.

$$\vec{B} = \mu_0 \mu_r(\vec{H})\vec{H}$$

$$\mu = \mu_0 \mu_r$$

$$\vec{B} = \mu\,(\vec{H})\,\vec{H} \qquad \text{(II.6)}$$

μ_o =permeability of free space.

μ_r=relative permeability.

μ =total permeability.

The electric field and current density are connected in the following ways:

$$\vec{J} = \sigma\vec{E}$$

σ = the electric conductivity [S/m].

II.4 Magneto-dynamic fields

Both Faraday's law (II.3) and Ampere's law (II.1) are applied in the magneto-dynamic formulation. The field problem can be calculated using potentials, just like in the magnetostatic situation. According to the magnetostatic scenario, there isn't much of a difference between the magnetic scalar and vector potentials in the two-dimensional situation. On the other hand, the magnetic vector potential can be applied throughout the domain in the magneto-dynamic scenario, while the magnetic scalar potential is only applicable to non-conducting areas of the domain. If the coupling issue is resolved, it is feasible to employ both magnetic scalar and vector potentials in various subdomains within the same investigated domain [22].

The same formula as in the magnetostatic situation applies to a non-conducting zone. In conjunction with the constitutive relations (II.4) and (II.6), a conducting zone necessitates the solution of Maxwell's equations (II.1), (II.3), and (II.2).

$$\nabla \times \mathrm{E} = -\frac{\partial}{\partial t}\nabla \times \mathrm{A} \qquad \text{(II.7)}$$

Or this equation can rewrite this way:

$$E = -\frac{\partial A}{\partial t} - \nabla V \tag{II.8}$$

where V is the electric scalar potential. The addition of the term $-\nabla V$, stems from vector calculus since $\nabla \times (\nabla \cdot V) = 0$. Using the constitutive relations in (II.6), the total current density in a conductive material (e.g., solid conductors) can be expressed as:

$$J = -\sigma \frac{\partial A}{\partial t} - \sigma \nabla V \tag{II.9}$$

The two main components of this equation are the source current density $J_e = -\sigma \frac{\partial A}{\partial t}$ and the eddy current density $J_o = -\sigma \nabla V$ In general, for a conducting domain, the field equation may be formulated in terms of the A-formulation or the A-V formulation. The field equation is represented as follows in the A-formulation:

$$\nabla x\ (\nu\ \nabla x\ A) + \sigma \frac{\partial A}{\partial t} = 0 \tag{II.10}$$

The field equation can be represented as follows if the conducting region has both the source and eddy current densities available:

$$\nabla x\ (\nu\ \nabla x\ A) + \sigma \frac{\partial A}{\partial t} + \sigma \nabla V = 0 \tag{II.11}$$

This kind of formula is called an A-V formulation. The following equation needs to be met in the conducting domain in order for there to be a unique solution for (II.10):

$$\nabla \cdot \left(-\sigma \frac{\partial A}{\partial t} - \sigma \nabla V\right) = 0 \tag{II.12}$$

According to [23], an equation in **V** can be obtained by setting $\nabla \cdot \left(-\sigma \frac{\partial A}{\partial t}\right) = 0$ in (II.11), which can then be calculated in advance using the known voltages or currents. This makes it possible to state the field equation in (II.11) only in terms of **A**. The resulting **A** is referred to as a modified vector potential.

The Lorentz's gauge, which may be expressed as follows, is the gauge method typically employed for solving mixed formulation issues.

$$\nabla \cdot A = \pm \mu \sigma V \tag{II.13}$$

Equation (II.10) can be solved using this to remove **V**, leaving a field equation that is expressed only in **A**. The gauge becomes the Coulomb gauge in non-conducting regions.

All these magneto dynamic formulations are subject to boundary and interface conditions in the same way as in the magnetostatic case

II.5 Definition of the finite element method

A numerical method called the Finite Element Method (FEM) is used to approximate solutions to boundary value issues for partial differential equations, it involves dividing a complex problem into smaller, simpler elements, where the behavior of each element is described by a set of equations. These equations are then combined to form a system of equations that can be solved to approximate the solution to the original problem. The FEM allows for the analysis of structures, fluids, heat transfer, and other physical phenomena by discretizing the domain into finite elements. The method is widely used in engineering and applied sciences due to its versatility and ability to handle complex geometries and material properties, the FEM is based on the principle of minimum potential energy and utilizes the calculus of variations to derive the governing equations for the problem. Error analysis procedures are employed to assess the accuracy of the numerical solution obtained using the FEM, the method has been extensively studied and refined over the years to address issues such as spurious modes and singularity in the solution. The FEM is a powerful tool for solving a wide range of problems in various fields of science and engineering [24], [25], [26], [27].

II.6 Definition of ANSYS software

Engineering simulation software like ANSYS provides solutions for product modeling with unparalleled scalability and extensive Multiphysics capabilities. It offers solutions for structural FEA analysis, fluid simulation, high-frequency electromagnetic modeling, and more. It is used for product design, testing, and operation. Finite element analysis (FEA) of a variety of mechanical issues is made possible by ANSYS software. With more than 50 years of experience, ANSYS is a leader in engineering simulation and has enabled software-defined vehicles. One high-performance interactive software program that uses FEA for electromagnetic analysis is called ANSYS

Maxwell. All things considered, engineers and designers can use ANSYS as a flexible tool to handle challenging engineering challenges in a variety of industries.

II.7 Conclusion

The conclusion for the chapter on electromagnetism and the Maxwell equations involves eliminating the magnetic field using specific equations. This procedure improves our comprehension of the interactions that Maxwell's equations describe. Maxwell's equations are solved numerically by applying the finite element method, which offers a mechanism for modeling electromagnetic processes. Researchers can examine and forecast electromagnetic impacts in a variety of situations by using these techniques. All things considered, the chapter offers a thorough review of the fundamentals and uses of electromagnetism, highlighting the importance of Maxwell's equations and finite element calculations in comprehending and forecasting electromagnetic interactions

III Chapter three

Optimization and Industrial applications

III.1 Introduction

Optimal machine geometry and control strategy are used to maximize the total static average torque or decrease the torque ripple in switching reluctance motor designs. However, for a commercially viable variable-speed SRM, the design goal is not only to meet the torque requirements at both low and high speeds, but also to minimize the total cost of the motor and power electronics. This thesis presents the torque optimization of a SRM by Ansys. The effects of different rotor and stator shapes and sizes on the performance were investigated. shapes are analyzed keeping the same ampere-turns for various SRM shapes, 8/6 poles base design, with various configurations as follows:

- Changing the factor of the rotor and stator.

III.2 Machine parameters

The machine calculated is a 8/6 SRM. Its dimensions are summarized in Table III.1.

the parameters	**Symbols**	**Value and unity**
number of stator	N_s	8
Number of rotor	N_r	6
Length	L	65mm
Stator Outer diameter	S_{out}	120mm
Stator Inner diameter	S_{out}	75mm
Rotor Outer diameter	R_{out}	74mm
Rotor Inner diameter	R_{inn}	30mm
Rotor Dia gap	R_{DG}	74mm
Stator Dia gap	S_{DG}	75mm
Yoke thickness stator and rotor	Y_{thick}	9mm
Rated output Power	P_{out}	550w
Frequency	F	50Hz
Reference speed	N	3500rpm
Rated voltage	U	48v
Embrace factor rotor and stator	$\boldsymbol{\varepsilon_r}$, $\boldsymbol{\varepsilon_s}$	0.5

Table III-2: Geometrical parameters of the machine

A picture of the switched reluctance motor after entering the parameters in ANSYS software

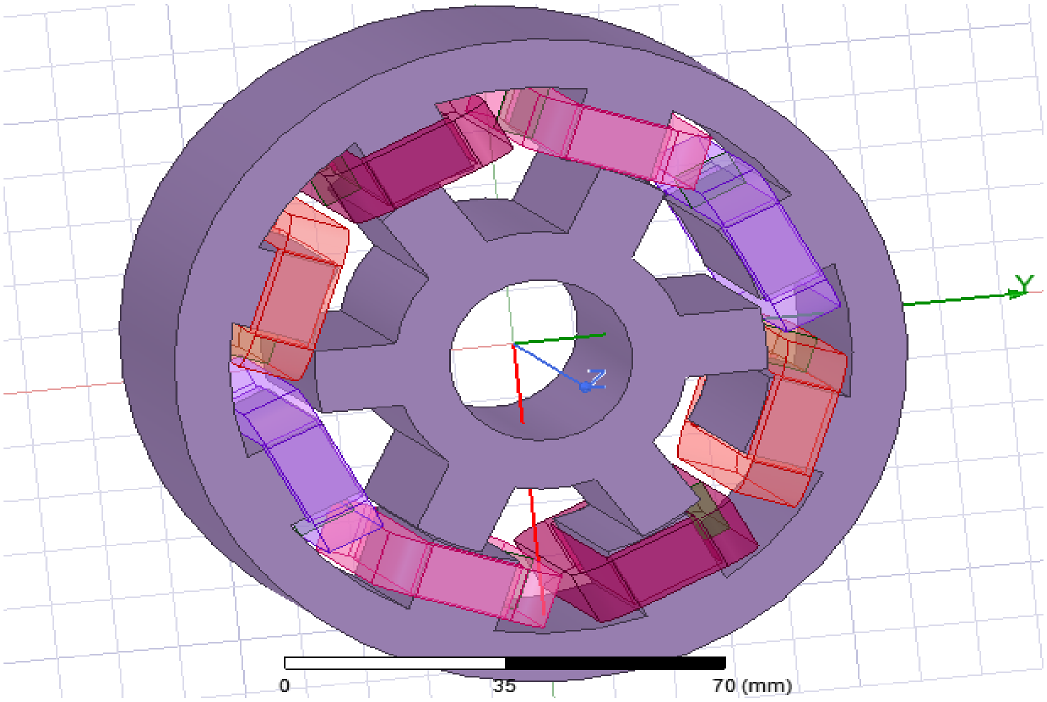


Figure III.7: model SRM 6/8 3D

III.3 Finite element analysis of SRM models

III.3.1 Mesh opération

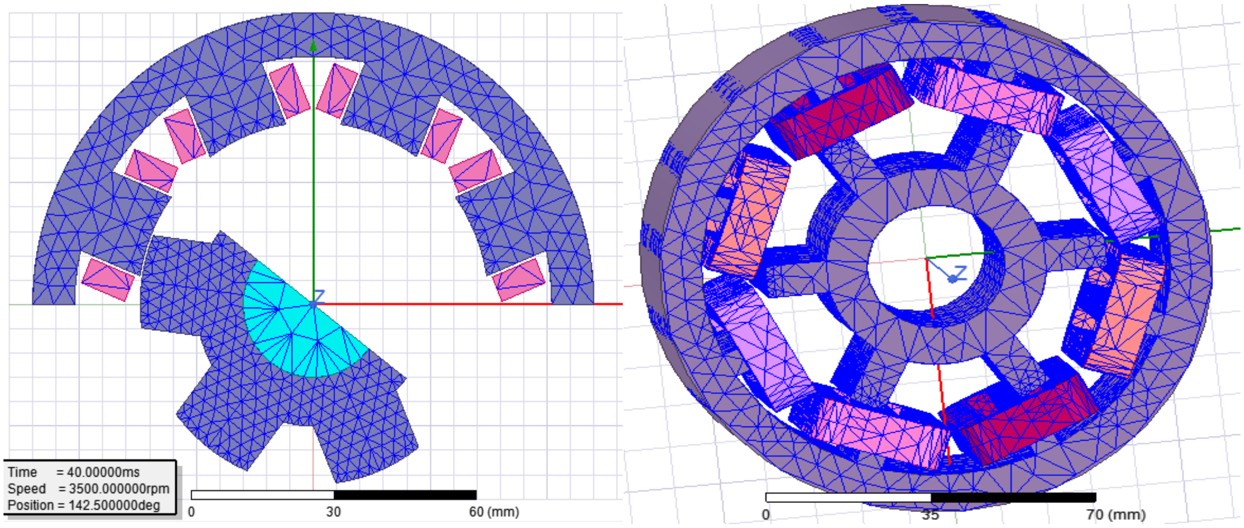


Figure III-8: Discretization of mesh elements 2D and 3D.

The figure III-8 displays the 2D and 3D discretization of the mesh for a switching reluctance motor. It shows how the geometry of the motor is broken down into smaller components, or cells, for numerical analysis with finite element methods. A key component of motor behavior simulation in programs such as Ansys is discretization.

Here's what we can see:

- **The mesh is made of triangles**: Because these elements are easily adapted to complex geometries, they are often used in finite element analysis.
- **The colors represent different properties**: These most likely represent the magnetic flux density, material characteristics, or other pertinent quantities.
- **There are two views**: a part that is magnified and may be focused on the stator or rotor, as well as the entire 2D image of the motor.

III.3.2 Magnetic flux density

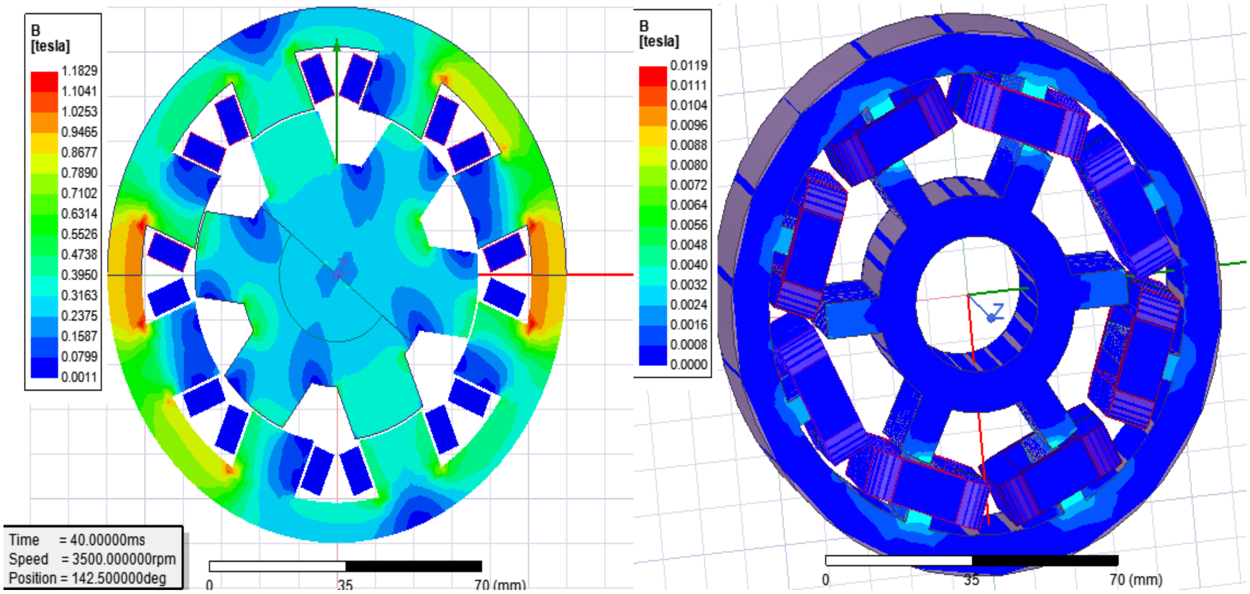


Figure III-9: magnetic flux density ($\vec{B}$) 2D and 3D.

The figure III-9 shows the results of an Ansys magnetic field simulation for a switched reluctance motor. The results are presented as a 2D and 3D plot of the magnetic field strength ($\vec{B}$) within the motor.

- **2D Plot:** The 2D plot on the top shows the magnetic field distribution within a cross-section of the motor, the magnetic field's strength is shown by the color gradient. Red areas indicate higher magnetic field strength.

- **3D Plot:** The 3D plot below shows the magnetic field in a more complete representation.

III.3.3 Flux lines

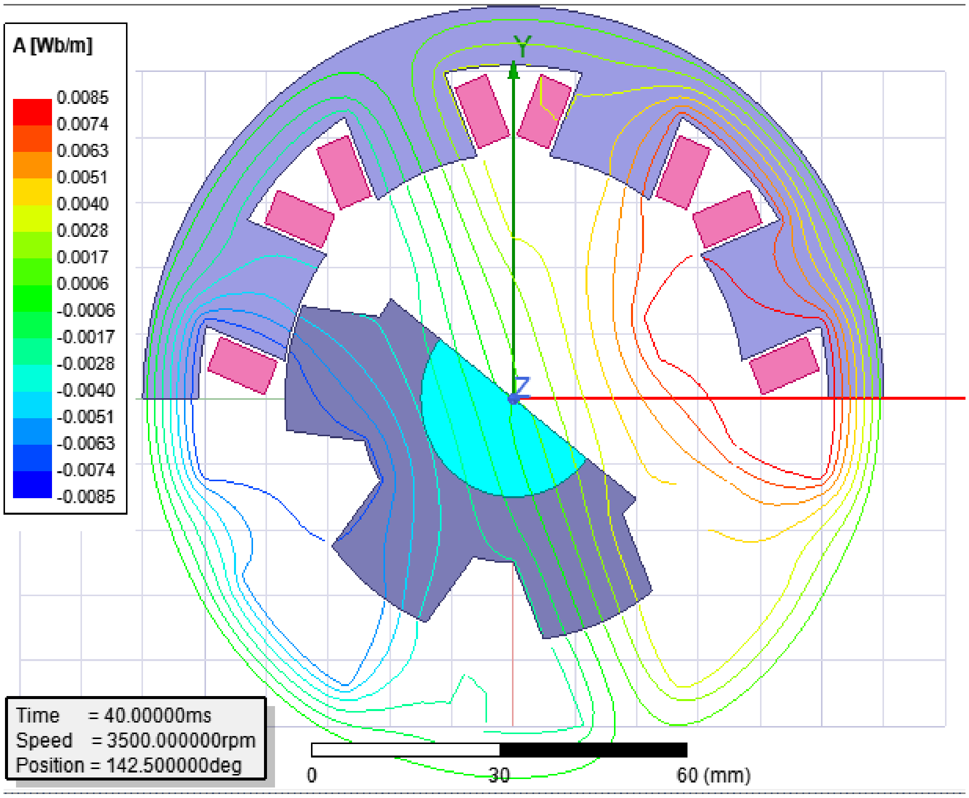


Figure III-10: magnetic flux lines ($\vec{A}$) in 2D

The figure III-10 shows a switched reluctance motor's magnetic field. The lines represent the magnetic field strength, with red being strong and blue being weak. The magnetic field is focused around the motor's rotor, which is highlighted in blue.

III.3.4 The results curves

The results in normal case embrace stator and rotor 0.5.

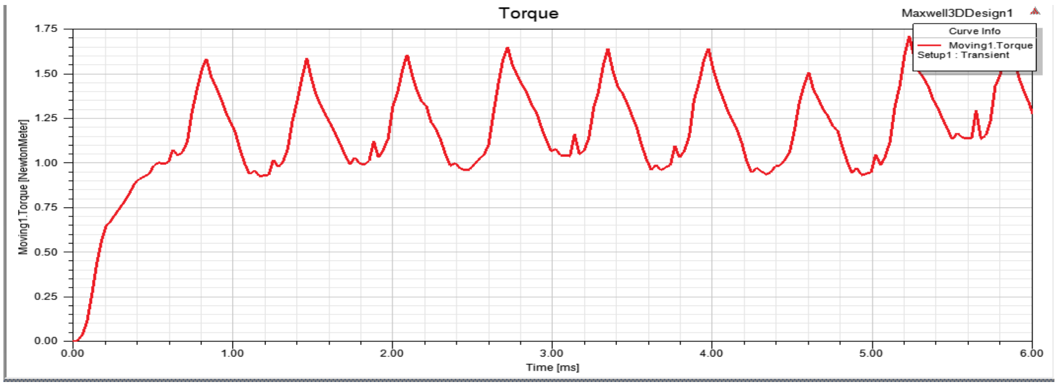


Figure III-11: Transient moving torque

The torque produced by the motor goes up and down, which means the motor is working in both ways, pushing and pulling.

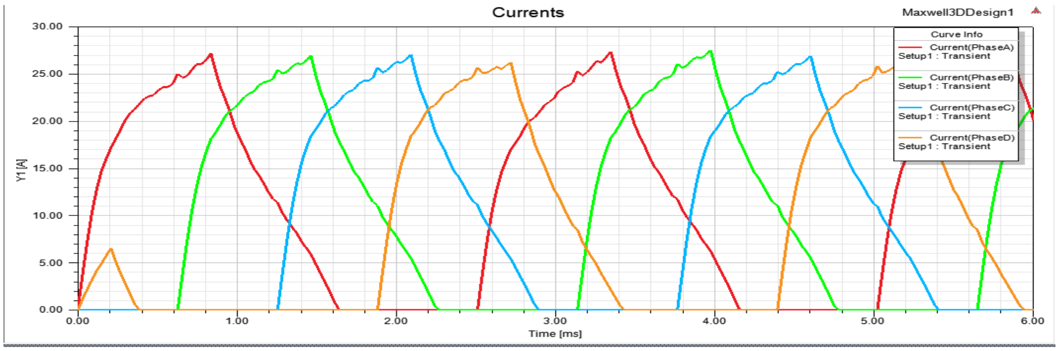


Figure III-12: Phase currents

The current in the motor's wires goes up and down, which means the motor is using and producing electricity.

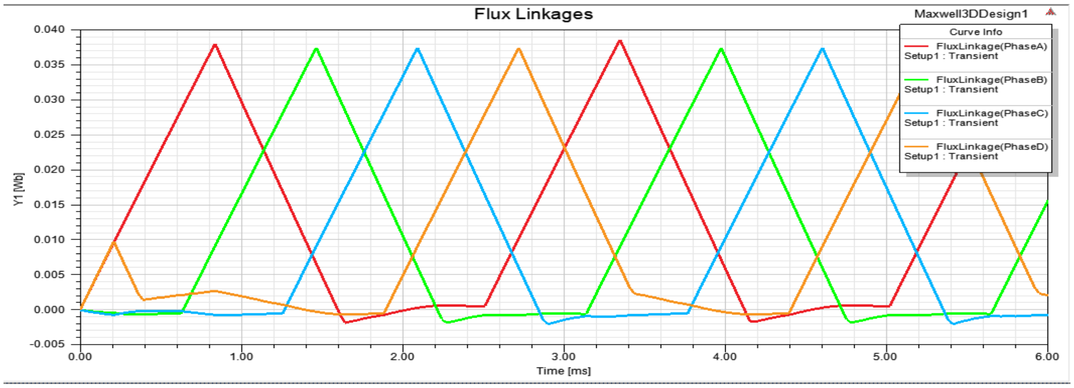


Figure III-13: flux linkages

The magnetic field in the motor goes up and down, which means the motor is working and changing the magnetic field.

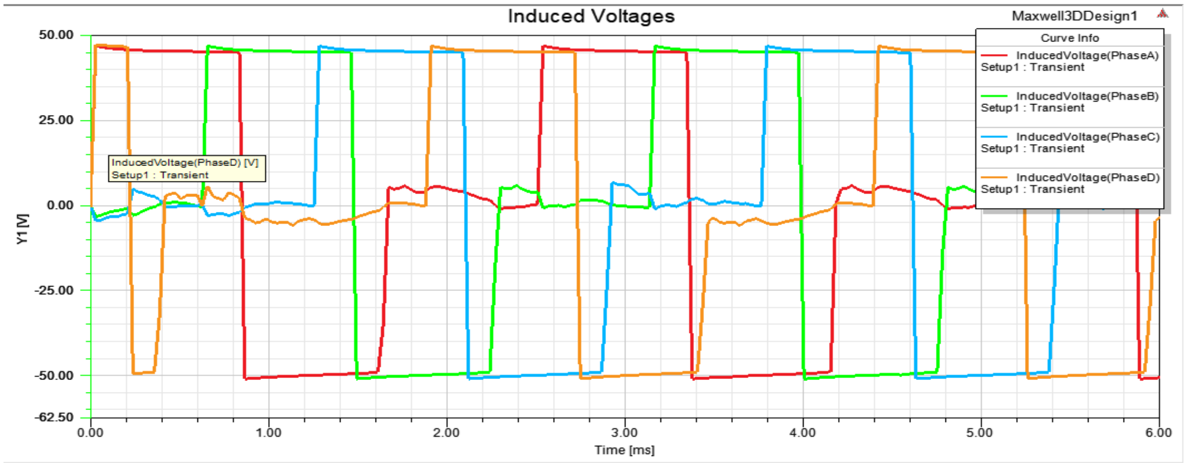


Figure III-14: induced voltages

The voltage in the motor goes up and down, which means the motor is producing electricity and using it.

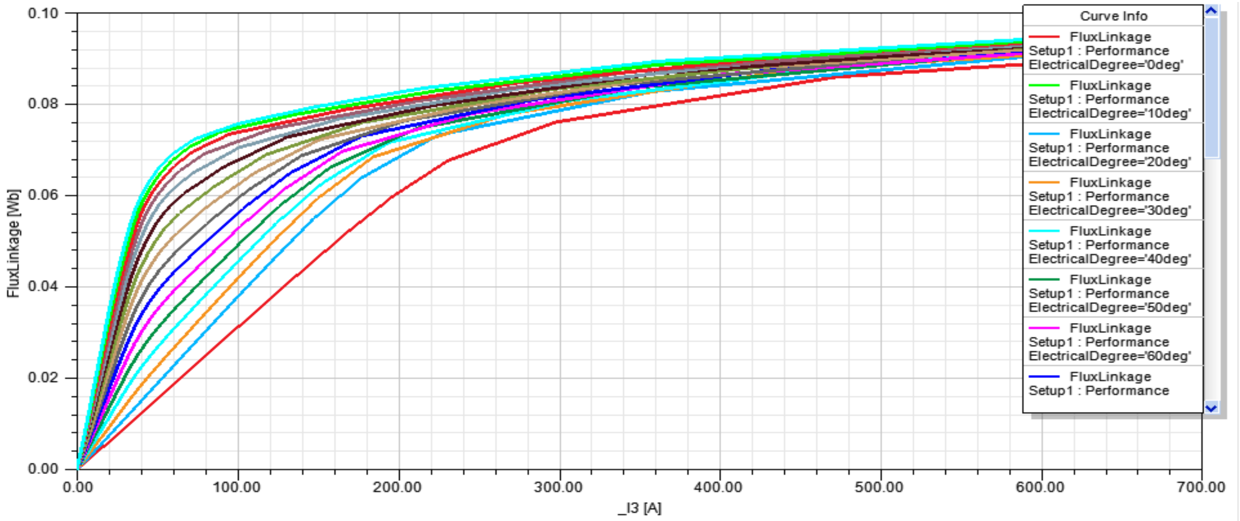


Figure III-15: Magnetization characteristics of designed SRM model.

The figure III-15 can be divided into three regions: deep saturation, saturation, and unsaturated.

As the electrical degree angle increases. the flux linkage curves shift higher, showing that the rotor position significantly affects the magnetic circuit.

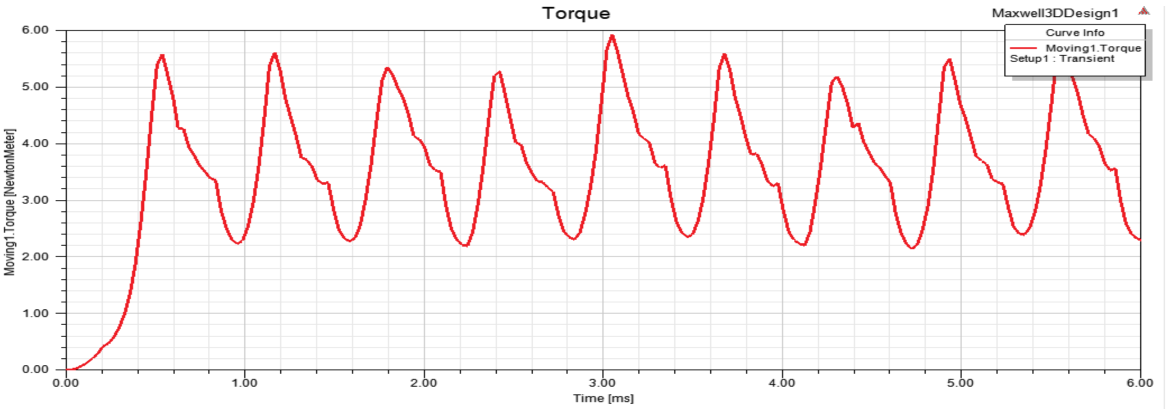
The flux linkage curves can be used to calculate the torque produced by the SRM, with the maximum torque resulting at electrical angles between 30 and 40 degrees.

The maximum current that may be delivered to the windings is limited since the magnetic core saturates at about 10 A.

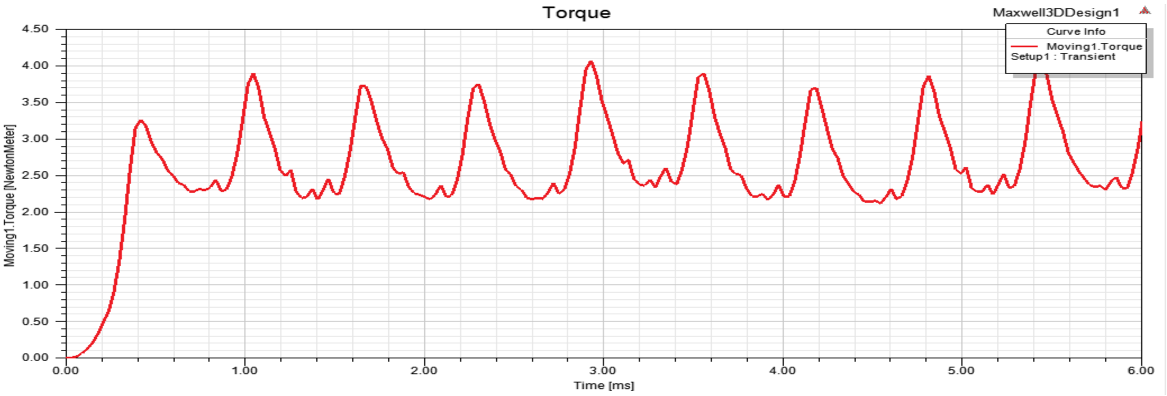
To minimize core losses and improve efficiency, the unsaturated area (I < 5 A) should be the target operating region for the SRM design.

III.4 The effect of embrace factor

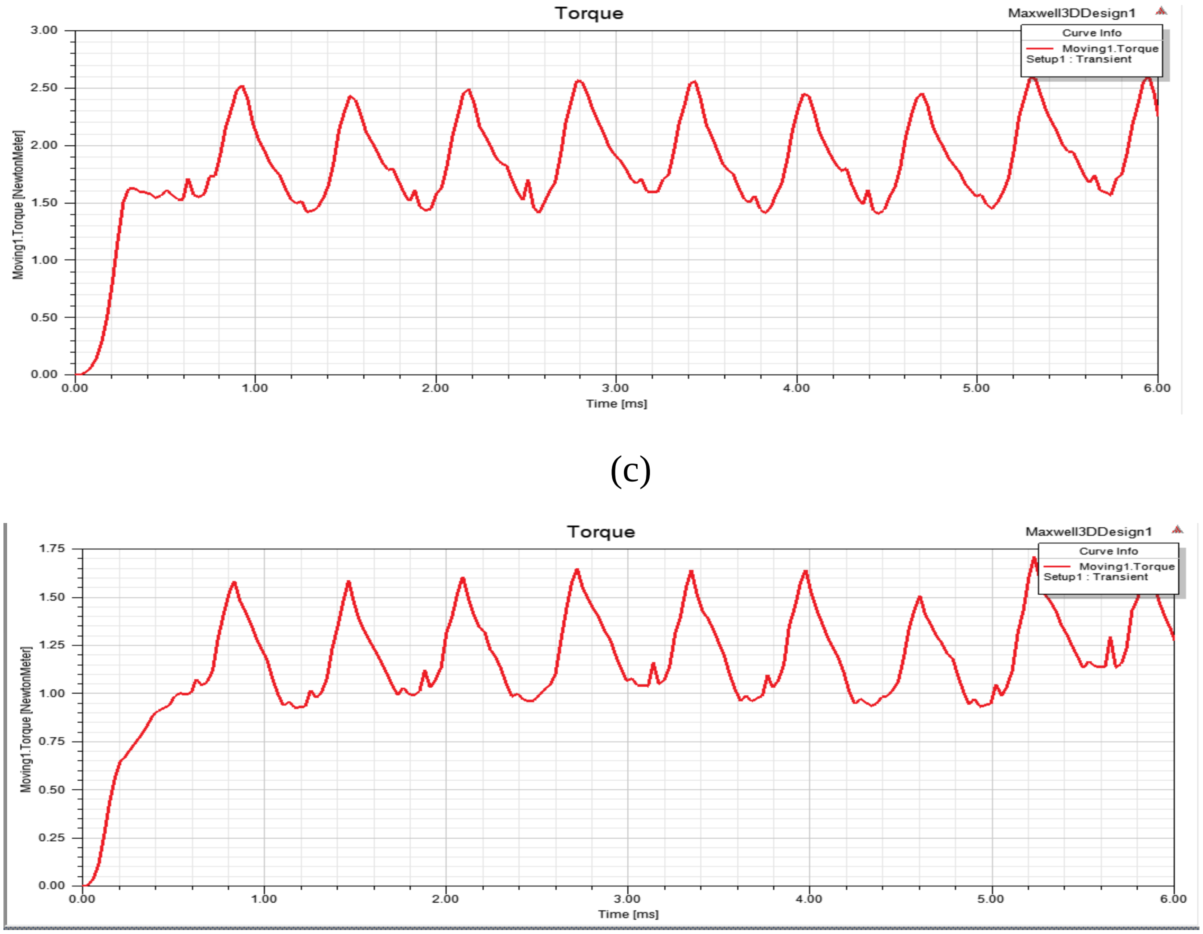
The figures III.16 present the variation of embrace factor from rotor. The simulations run with the few combination of pole embrace to achieve highlighted condition.



(a)



(b)



(c)

(d)

Figure III-16: Variation of rotor embrace factor.

(a) : $\boldsymbol{\varepsilon}_{\mathbf{r}}$=0.2 , (b) : $\boldsymbol{\varepsilon}_{\mathbf{r}}$=0.3, (c) : $\boldsymbol{\varepsilon}_{\mathbf{r}}$=0.4, (d) : $\boldsymbol{\varepsilon}_{\mathbf{r}}$ =0.5

In this study, the effect of pole embrace was investigated and given parametrically as in Table III.3

Stator	**Rotor**	**Torque ripple (%)**
0.5	0.2	57.81
	0.3	42.307
	0.4	**33.33**
	0.5	25.00

Table III-3: The embrace factor of rotor.

In similarly we present the variation of embrace factor from stator in this case, so we suffice with studying and we calculate every torque ripple in Table III.4.

Rotor	**Stator**	**Torque ripple (%)**
0.5	0.2	75.00
	0.3	41.00
	0.4	**29.41**
	0.5	25.00

Table III-4: The embrace factor of stator.

In conclusion, we note from this study that the torque ripple improves with the increase in the factor so in other hand we have the lowest torque. We can see the best choice is 0.5 rotor embrace factor and 0.4 stator embrace factor because we are high torque and low torque ripple.

III.5 Industrial applications of this type of power motor 550W and 3500tr/min:

The SRM 500W motor at 3500 rpm is a relatively small electric motor, but with a fairly high rotation speed. Here are a few industrial applications suitable for this type of motor:

Light-weight machine tools:

Milling machines, lathes, drills and other light machining equipment.

Suitable for small to medium-scale operations requiring high rotation speeds for precise cuts.

Pumps:

Small to medium-sized water or oil pumps.

Ideal for fluid circulation and transfer systems.

ventilators and blowers:

Used for ventilation and cooling applications.

Suitable for air conditioning or machine cooling systems.

Light industrial robots:

Actuators for small robots in assembly or handling applications.

Used in industries requiring fast and precise movements

Laboratory equipment:

Centrifuges, mixers and other equipment requiring rapid rotation.

Ideal for research and development laboratories.

Small compressors:

Air compressors for pneumatic tools or pneumatic control systems.

Farm Equipment:

Small motors for agricultural machinery such as lawn mowers, sprayers or irrigation pumps.

Textile machinery:

Used in looms, spinning machines or other textile manufacturing equipment requiring high rotation speed.

These applications benefit from the combination of moderate power and high speed, allowing efficient performance in tasks requiring fast and constant rotation.

III.6 Example of application SRM motor for pumping water

To size a centrifugal pump for a motor with a mechanical output power of 550W and a speed of 3500 rpm, it is necessary to determine the pump characteristics (flow rate and head) that can be supported by this motor. Here are the steps to follow:

III.6.1 Calculating available hydraulic power

Available hydraulic power can be calculated from the motor's mechanical power, taking into account pump efficiency (ηp).

Efficiency considerations

For the calculations, we assume the following values:

- **Pump efficiency (ηp) :** 70% (0.7)

a) Available hydraulic power

The hydraulic power supplied by the pump is:

$Ph=Pm\times\eta p$

$Ph=550\ W\times0.7$

$Ph=550W\times0.7\ Ph=385\ W$

III.6.2 Determining flow rate and discharge head

Let's use the hydraulic power formula to determine the pump's characteristics:

$Ph=(Q\times H\times\rho\times g)\ /\ \eta p$

Where:

- Ph is hydraulic power in watts (W).
- Q is flow rate in cubic meters per second (m^3/s).
- H is discharge head in meters (m).
- P is fluid density in kilograms per cubic meter (kg/m^3), for water $\rho=1000\ kg/m3$.
- g is the acceleration due to gravity, approximately 9.81 m/s2.

To simplify calculations, we fix one parameter (flow rate or head) and calculate the other.

a) Determine flow rate and calculate discharge head

Assume a flow rate of $Q=200\ l/min=0.00333\ m^3/s$

$Ph=Q\times H\times\rho\times g$

$385\ W=0.00333\ m^3/s\times H\times1000\ kg/m3\times9.81\ m/s2$

$H=385\ W\ x\ 0.00333\ m^3/s\times1000\ kg/m3\times9.81\ m/s2$

$H\approx11.76\ m$

So, for a flow rate of 200 l/min, the maximum head this pump can deliver with this motor is around 11.76 meters.

b) Determine discharge head and calculate flow rate

Assume a discharge head of H=30 m.

$Ph=Q\times H\times \rho\times g$

$385\ W=Q\times 30\ m \times 1000\ kg/m3 \times 9.81\ m/s2$

$Q=385\ W/ (30\ m\times 1000\ kg/m3\times 9.81\ m/s2)$

$Q\approx 0.00131\ m^3/s$

$Q\approx 78.6 l/min$

So, for a discharge head of 30 meters, the maximum flow rate this pump can deliver with this motor is around 78.6 l/min.

III.6.3 Conclusion

For a 550W motor at 3500 rpm, here are the combinations of flow rate and head that the centrifugal pump can handle:

- **Flow rate of 200 l/min** with a delivery head of approx. 11.76 meters.
- **Delivery head of 30 meters** at a flow rate of approx. 78.6 l/min.

III.6.4 Recommandations

1. **Choose the right pump:** Consult the performance curves of specific centrifugal pumps to ensure that they can operate under the specified flow and head conditions.
2. **Check pump specifications:** Ensure that the chosen pump is compatible with the motor's power and speed capabilities.
3. **Consider actual operating conditions:** Take into account variations in flow and pressure, as well as additional pump characteristics (NPSH, materials of construction, etc.) for optimum selection.

III.7 Conclusions

This report presents research on the effects of the stator and rotor's pole embrace factor (ε_s and ε_r) on the performance of SRMs used for off-grid water pumping applications. Optimization of Switched Reluctance Motors involves a multidisciplinary approach, combining advancements in design, control, thermal management, and noise reduction. The results from optimized SRMs demonstrate significant improvements in performance, making them more competitive and suitable for a wider range of applications. Future research in this area will continue to push the boundaries, focusing on further enhancing efficiency, reducing costs, and improving the user experience.

General conclusion

In conclusion, we have demonstrated the potential of Switched Reluctance Motors (SRMs) for off-grid water pumping systems, highlighting their advantages in terms of high torque-to-inertia ratio, high efficiency, and low production and maintenance costs. Through our research, we have gained a comprehensive understanding of the underlying principles of SRM operation, including the effects of electromagnetism and Maxwell's equations. Furthermore, our investigation into the influence of stator and rotor pole embrace factors on SRM performance has revealed the importance of optimizing these parameters to achieve improved efficiency and competitiveness. Specifically, our results show that a rotor embrace factor of 0.5 and a stator embrace factor of 0.4 achieve a balance between high torque and low torque ripple, minimizing unwanted vibration and improving overall performance. This optimization is crucial for many applications, where both high power output and low vibration are desired. We believe that our findings have significant implications for the design and development of SRMs, and we are confident that continued research in this area can unlock new opportunities for sustainable development and improve the lives of millions of people around the world, particularly in off-grid and rural areas where access to clean water is limited. Overall, our study has contributed to the advancement of SRM technology, we making SRMs an attractive solution for industrial water pumping systems. We envision the widespread adoption of SRMs in industries such as agriculture, mining, and manufacturing, where water pumping is a critical component of operations. The use of SRMs in these applications can lead to significant energy savings, reduced downtime, and lower operating costs, ultimately contributing to a more sustainable and environmentally friendly industrial sector

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