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STUDY AND SIMULATION OF HIGH COMPETENCE SWITCHED RELUCTANCE MOTORS

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ABSTRACT

Applications due to the simple and robust structure, among the various types of motor one of the most popular motor which is use commonly known as "SRM". Features of SR Motor which make this more attractive among the all type of motors are high torque density, efficiency, and reliability, coupled with their fault tolerant structure, low manufacturing cost and simple physics. The main parts of the motor are stator, rotor and stator windings. It has simple concentrated stator windings on the stator pole which are excited individually by dc supply and rotor has no windings or magnet, it is also called doubly salient pole motor. This type of motor works on the principle of variable reluctance between stator and rotor. Variation in reluctance values between Rotor rotations is primarily caused by the stator and rotor. Despite their many benefits, SR motors are not commonly utilised in a variety of applications due to a number of inherent drawbacks, including significant torque ripple, vibration, and noise pollution. Many researchers are working at their respective levels to ensure that the SR Motor meets the demands of the industrial application.

Motors, stepper motors, and motors with resistance. Rotor rotation is primarily caused by the stator and rotor. Despite their many benefits, SR motors are not commonly utilised in a variety of applications due to a number of inherent drawbacks, including significant torque ripple, vibration, and noise pollution. Many researchers are working at their respective levels to ensure that the SR Motor meets the demands of the industrial application.

Keywords: Rotors, Reluctance, Synchronous, Windings, Motors

I. INTRODUCTION

Any country's overall socioeconomic development is heavily influenced by its ideal energy source's subservience. Energy is the most vital component for the comfortable extension and improvement of citizen life, which is crucial for long-term global economic assessment. Energy is necessary for all living things to exist. Human energy decisions have an impact on the entire natural system of the earth. These repercussions may have a major impact on the standard of living for both humans and other living things on Earth. Electricity is the most hygienic, adaptable, and controlled energy source currently available, making it a prime option for long-term use. Energy in the form of electricity is essentially non-polluting, practically clear, loss-free, and clean. The process of converting one set of current, voltage, and frequency values to another set of the same values is known as electrical energy conversion. One of the most crucial accessories that is a necessary component of any regular application in everyday life is the electrical motor. A perfect motor must have the following qualities to handle the delicate and sporadic live wire application: maximum efficiency, best performance, minimal losses, low heating, ideal operation, and micro control over mechanical motion. An electric motor is an electromechanical device that uses electrical energy to create rotational force, which is then transformed into mechanical energy for use in other applications. Creating the perfect electrical motor with the right features is a difficult goal for researchers everywhere.

1.1 Working Principle and Classification

Switched reluctance motor [25] is a robust structured machine due to the absence of slip ring in rotor. No supply is needed to be given for exciting the rotor of SR motor. This offers numbers of advantage due to its structure and is useful in much application like industrial application, corporate application and domestic application. Due to working principle of SR motor, motor inherits certain vulnerabilities which are needed to be addressed. Ripple in rotor rotation, poor efficiency, large size and heating in stator body is some important aspect needed to be worked upon. In this chapter, working principle of SR motor, construction aspect of SR motor [26], important construction features of SR motor is presented. Effect of different pole construction, their advantages, disadvantages and application of such construction in enhancing effacing, controlling ripple and speed of SR motor is also covered.SR motor always operates in continuous switching mode. In SR motor, stator of motor and rotor of motor both have changeable magnetic circuit in context of reluctance. That's way SR motor is assumed to be truly reluctance motor. It is a double salient motor. SR motor can be considered as stepper motor. This motor used in different applications especially in case when rotary or linear motion is required. The rating at which SR motor operates is very high voltage and very high current at constant speed which is synchronous speed [30].

1.2 Classification

Switched Reluctance Motor has doubly-salient structure with singly excited stator windings that are excited individually in proper sequence. The rotor of the SRM has no any windings, magnet, or cage. SRM is implemented with a stack of laminations of salient pole. Difference of the changing reluctance in between air gap of machine between stator and rotor is prime factor which is responsible for rotating torque produced in the SR motor [96]. Fig. 1 shows the typical structure of the SR motor.

Rotating angular motion is produced because of the difference of reluctance variation present in air gap of rotor and stator of machine [96]. A typical SRM structure is depicted in the Fig. 1. From the picture this is very much clear that the structure of rotor and stator both are of salient pole construction. This feature makes motor a double salient machine of higher rating.

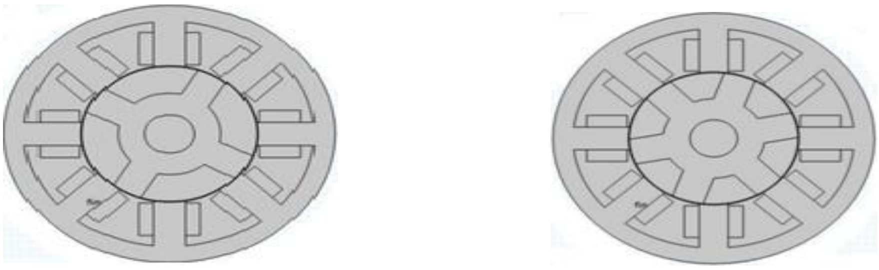

Fig 1: Diagram of 8/4and 8/6 pole SRM

SR motors can be divided into two different classes (as shown in Fig. 1):

1. Rotary type switched reluctance motor
2. Linear type switched reluctance motor

Rotary type switched reluctance motorcan sub classified into two different types as per the path of magnetic field in the air gap of motor:

1. Radial field SRM- Magnetic field is perpendicular to the shaft
2. Axial field-Magnetic fieldis in shaft axial direction

SRM can also sub classified on the basis of coil of the phase in stator :

1. Shorter flux path SRM
2. Longer flux path SRM

1.3 Axial Flux SR Motor

The path of flux in the air gap is allied with the axis of the motor in these types of motor. When in specific application, if length of motor is important, this is an ideal motor to be used. Also in case if high torque is required at stating with high pick up, such as air condition fans, electrical vehicles, these motor frequently used.

Redial Flux SR motor is most frequently used model in SR motor classes. Short path SR motor and Conventional SR motor is sub classes of these motor. In conventional SR motor, poles facing each other are connected with each other in series to create resultant phase in space. In short path SR motors, neighboring poles are interconnected with each other to form a magnetic circuit to create resulting phase in the air gap.

1.4 Hybrid Excited SR motors

In such category of SR motors, a permanent magnetic excitation is used in combination with transient variable excitation which is provided from electrical source to the stator poles of SR motor. This combination offer very important features and characteristics to these types of SR motors [96]. These motor are an ideal motor to be used in wind turbine application where the source of electrical energy is a criterion due to location. Following are the advantages:

1. There is flexibility to control the air gap flux in the SR motor by the application of variation in DC source which is connected with the stator winding. The polarity can also be controlled so as to control the flux
2. The performance and the efficiency of these kind of motor can be optimized for higher value by variation in combination of power supply and the permanent magnetic field present in the rotor of SR motor.

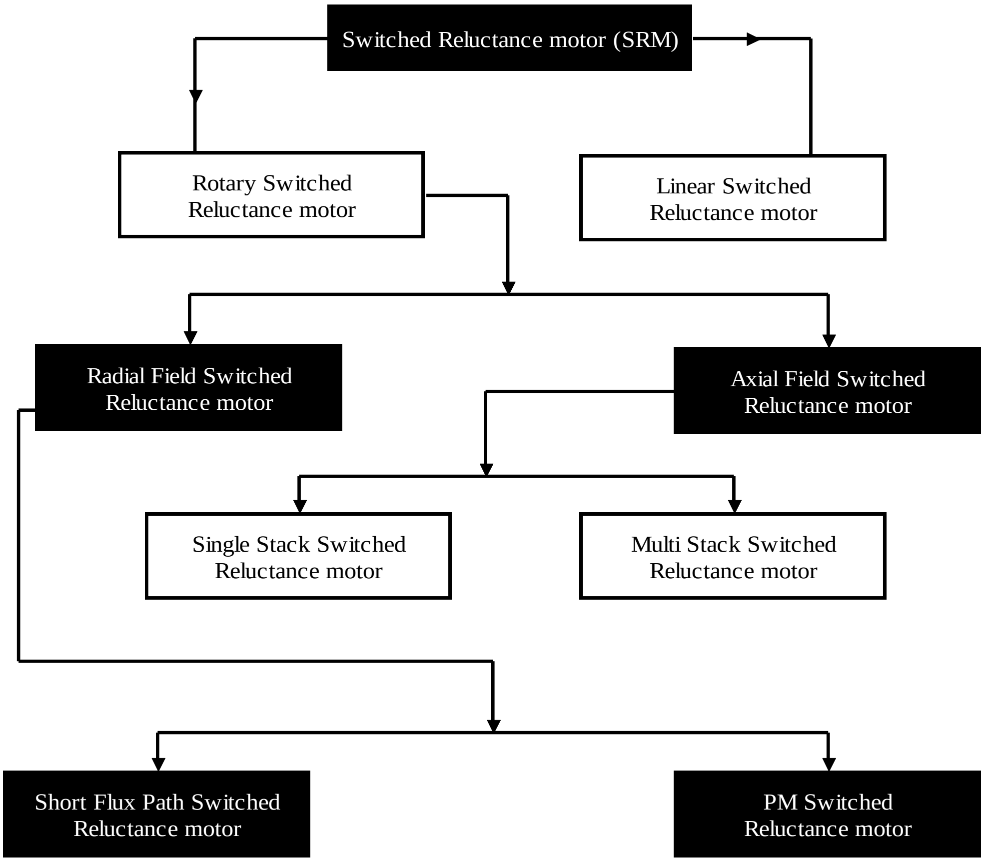

Fig 2: Classification of Switched Reluctance Motor

II. LITERATURE SURVEY

The second book [10] authored by Miller (1993) entitled "Brushless Permanent-Magnet and Reluctance Motor Drives" explains all the features of SR motor drive in more detail. This book also depicts the qualitative aspects of SR motor in a very judicious manner without exaggerating the facts. Besides the potential of SR motor drives, the limitations are also well covered and that gives a good insight to a researcher about the state-of-the-art of this motor. After the publication of Miller's book, lots of work has been done on the various aspects of SR motor, like design, modeling, control, position/shaft sensor less operations, torque ripple minimization, acoustic noise reduction etc.

In a different control techniques; optimal profile for motor inductance were considered. But in most of the cases, none of them have taken effect of the coefficient of mutual induction in to consideration. J. C. Moreiaraet.al. (1989) mentioned the consequences of the coefficient of mutual induction were in [13] and H. H. Moghbelli et.al. (1988) in [14] but a controller to compensate the consequences wasn't proposed. The likelihood of two-phase excitation was introduced by P. Pillayet. (1999) shown in [20] but it also only mentioned the consequences of mutual coupling without suggesting any active control scheme to beat the consequences. In some applications, the torque ripple caused by the coefficient of mutual induction might not be acceptable.

Therefore, the effect of mutual coupling should be analyzed to make a decision whether it's negligible or not, additionally, J. Faiz [1] in 2000 had many attempts to decrease the torque ripple using advanced electronics control techniques including optimization of controlling parameters like supply voltage, commutation angles and current level [27]. One among the old methods for torque ripple reduction uses torque/ current/rotor angular angle characteristics to regulate SRM drive system.

In 1991-92 these characteristics are often obtained using theoretical methods by R.C. Kavanagh and D.S. Schramm [27] or by J.C. Moreira had performed the static test [28] then apply interpolation routine. Some methods attempt to reduce torque ripple through compensation, deformation and current optimization.In1996 , I. Husain , PWM control technique has been used to improve the current in which the current traces a contour to develop a constant torque [29]. The suggested technique is more appropriate at low speeds range. By N.C. Sahooet. all, in 2000-01, Current compensation has been used in [30]. To generate current profile, Fuzzy-logic method has been applied in [30] which compensate the non-linearity of the system well. In [31], reference current is modified through adding output of a fuzzy-natural compensator by J.A. Dente. In 2011, by L. Kalaivaniet. all, phase current compensation has been implemented by fuzzy-logic controller and ANFIS, which leads to good results up to the base speed [32]. By R. Mitra, Phase current shaping method has been utilized in [33, 34]. In 2001, by I. Agirmet.all. Phase current is often improved by injecting and adjusting proper harmonic terms within the current and cancelling the harmonics [36].

For minimizing the torque ripple and obtaining high performance an appropriate speed controller design has been suggested by H. Tahresima in 2011[38]. In [39], controlling sum of square of phase currents plus sliding mode control has been recommended by N. Inanc in 2003. In [40], phase current optimization method during a positive semi-sinusoidal form and its control has been employed by N.T. Shaked, in 2005. In 2009 by R. Gobbiet, et. all.[41], the hysteresis controller has been optimized so as to inject an appropriate current to the drive system. One another method is designing and obtaining particular current in [42]. Selection of optimal switching angles supported the utmost torque and current ratio criterion is acceptable for top speed SRM [42]. During this case, the minimum torque ripple criterions are often approximated over low speed range. Attempt has been made in 2003 by C. Mademliset.all. [43-47] to optimize on- and off-switching angles for reduction of torque ripple in SRM.

D.H. Lee in 2009 had introduce the torque sharing function technique could also be wont to alleviate the torque ripple [48]. This system controls torque variation rate over commutation period consistent with a pre-defined torque distribution function. In 2013, so as to require under consideration a particular non-linear model for inclusion of SRM drive non-linearity, advanced methods like artificial natural network (ANN), fuzzy-logic or their combination are often applied by J. Faiz [52, 53]. In Ann non-linearity of SRM characteristics is trained by NNs then current graph for ripple reduction is obtained by. In [54, 55], ANN has been used as an intelligent controller by Y. Cai in 2006-07 [54]. The fuzzy-logic model has the advantageous of straightforward mathematical computations in processing fuzzy-logic rules which results in a fast operation. Fuzzy-logic has been used as an intelligent method by M. Rodrigues in [56].in 2010, are often also used torque control techniques for torque ripple reduction [61]. A torque controller has been designed K. Russa and that I. Husain in 2002 in [64] while in [65] the ripple are reduced by controlling the excited phase output torque through adjusting the relevant co-energy by tracking the co-energy diagram by K.F. Wong in 2009 .

Direct torque control (DTC) has been followed in [66, 67]. A new pattern called two-phase excitation has been suggested in [68] by C. Ma 2013, which have the highest average torque and lowest torque ripple compared to the two conventional patterns. The attempt has been made in [70] to decrease the torque ripple through changing the geometry of the motor by D.H. Lee in 2013. In [71], a four-level converter has been utilized to improve the torque and speed ripple which also shorten the response time and current peak in SRM by J.W. Ahn in 2007 [71]. One of useful and efficient method in reducing the cost and enhancing efficiency is decreasing the losses and number of switches in each leg of the converter. A. Deriszadeh in 2011, has been introduced a new converter with one switch per phase in [72] which have low cost and high efficiency advantages as well as lower torque ripple. Novel and advanced methods and algorithms have been suggested by E. Daryabeigiet all, in 2014, in [73-76] in order adjust the speed or current controller and reduce the torque ripple.

III. METHODOLOGY

The phase coils are excited by the DC supply so that stator poles magnetized and create two opposite stator poles those causes the rotor poles move towards the minimum reluctance position and align with energized stator poles [56].

SR motor uses principle of ferromagnetic material free movement in the direction of minimum reluctance. Ferromagnetic material has property to alien them self in the direction of minimum reluctance. Rugged construction of SR motor is very favorable for difficult working environment. SR motor is capable of handling high heat and major vibration due to absence of winding on the rotor of motor [96].

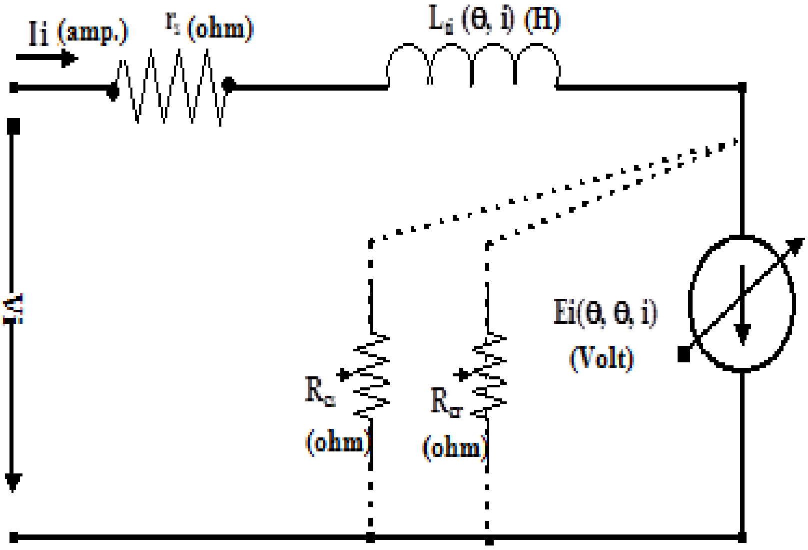

Fig 3: Core Loss based Equivalent Circuit of Switched Reluctance Motor [56]

A sample equivalent circuit of SRM is depicted in the Fig. 3 the circuit is modeled in core loss context of SRM. Mathematical model of SRM shows highly non linearity(as shown in Fig.3.4) because of the high saturation condition in rotor core of motor. Insignificance of inter-operability among phases of motor, the commutative effect of torque of phase can be calculated as in next equation [96].

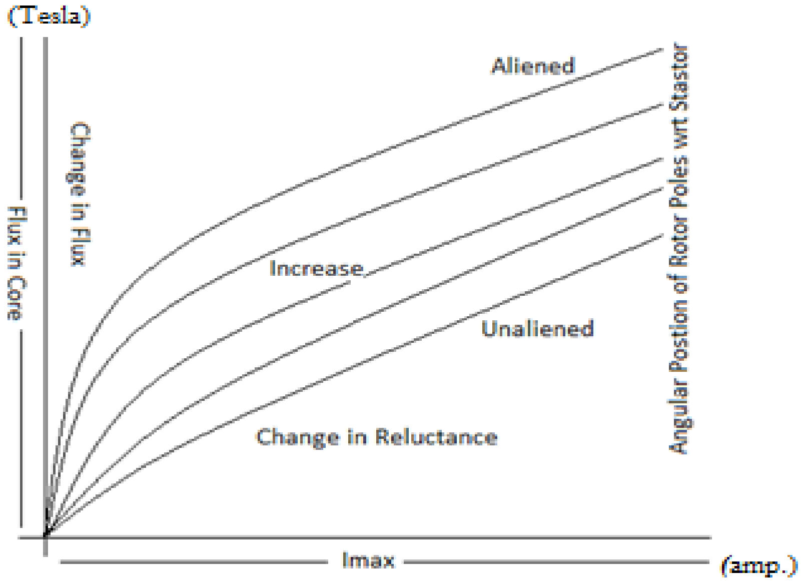

Fig 4: Change in Flux w.r.t Change in Rotor Position [96]

Fig. 4 (A) depicts that poles $r_1$and $r_1'$of SRM rotor and poles $s_a$and s_a' of stator in the coaxes.As soon current is passes through phase b of the SRM, as per the direction, flux is produced in the stator and air gap of SRM. In the case of 8/6 construction of switched reluctance motor, more numbers of rotor poles are in misalignment with stator poles. This is the reason, the resulting torque is sufficient to give rotator motion to the rotor shaft. If two poles of rotor are aligned with stator poles then 4 poles of rotor will out of alignment with stator poles. This group of poles will try to pull other poles to come to alignment, resulting in motion.

3.1 SR Motor Modelling with COMSOL

Research in all fields of discovery and invention of the modern world must include mathematical modelling and model simulation. Today's world is full of complex and sophisticated instruments that are used in almost every application. These instruments integrate multidisciplinary knowledge and information to successfully complete the objective task for which they are designed. Any change in a participating element's or material's property required in-depth analysis during testing in order to meet application expectations. It is nearly impossible to conduct such testing in the real world of work; even if it were possible, it would require a significant investment of time and resources that is not justifiable nor feasible. In this case, mathematical modelling and software simulation are crucial to the study.

Research on real-world applications has accelerated thanks to advancements in applied mathematics, which have made it easier for scholars to conduct additional studies using quick and easy methods (Fig. 5).

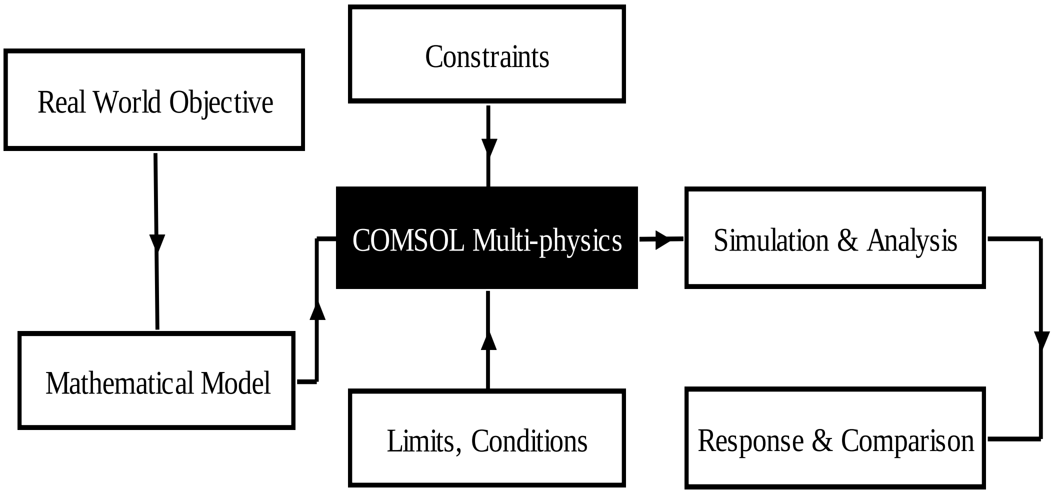

Fig 5: COMSOL Multi-physics Simulation Concept

The idea of a simulation environment is to create a virtual environment for response performance analysis and help in finding the best possible solution by transforming the concepts, limits, constraints, and conditions of real-world physical laws.

Software developers are pushing forward to create cutting-edge simulation and analysis software for various scientific and engineering streams, motivated by the expectations of research scholars in the modelling and simulation stream. Currently, a variety of modelling and simulation programmes are available to help researchers test and simulate novel concepts and inventions quickly, cheaply, and with high accuracy. AnyLogic, SimScale, and MATLAB. Arena and Simul-8. Among these programmes for modelling, simulating, and analysing novel concepts, theories, and research is COMSOL Multi-physics. compact, quick,

3.2 COMSOL Multi-physics

Multi-platform analysis and simulation software, COMSOL Multi-physics, is used to implement mathematical models and equations that represent various real-world tools, projects, and goals that must be realised in a virtual environment for comparative study and performance analysis.

Advanced finite element analysis in a simulation environment is made possible by the incredibly advanced simulation software COMSOL Multi-physics. The solver simulator that is integrated into COMSOL Multi-physics can realise multiple streams of science, technology, and engineering for analysis and response. The company that created the corresponding simulation and analysis software for complex model, control, and mathematical equation simulation and analysis is called COMSOL Incorporated. For academic and research purposes, scientists, researchers, and students can download the software for free. Additionally, free sample code support and an open source discussion forum are provided by COMSOL Inc. for academic and research purposes. For corporate and industrial use to test and simulate new models and projects, a licence version of the same is available.

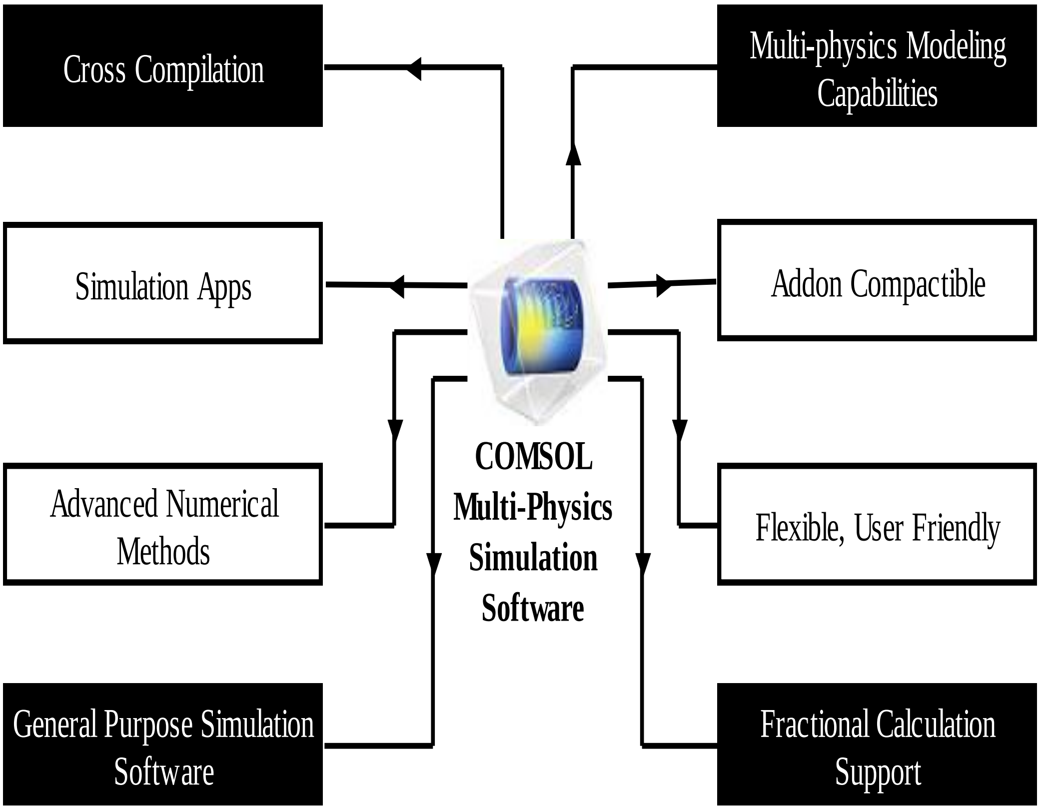

Fig 6: Characteristics of COMSOL

3.3 SRM Design Modification and Analysis

A software model for the Switched Reluctance motor (SR motor) has been created in the virtual IDE by CAD software with the aim of conducting the simulation and performance analysis of the motor. Every single component, including the air gap permittivity, core material, pole, winding material, stator winding, and other specifications, has been finalised. The SR motor specifies the dimensions, material type, and material properties. The SR motor's design is displayed in Fig. 6 and other places.

3.4 Teethed and multi-teethed stator pole design (Case- I)

For additional motor analysis in a virtual environment, we can plot the performance curve and response plot on the graph if the machine's stator pole design is altered but the rotor design remains unchanged. Multi-teethed stator pole SRM in Fig. 7 and teethed stator pole SRM as below are depicted in Fig. 8.

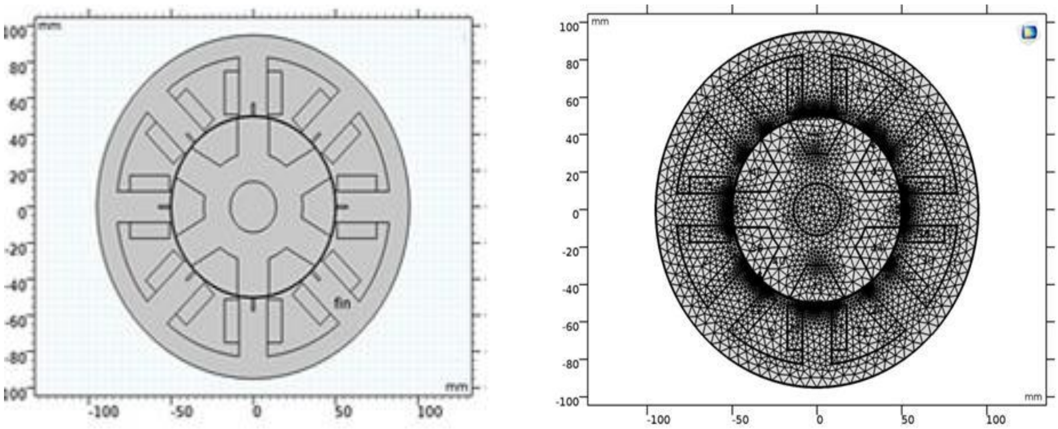

Fig 7: Design & Meshing Of Teethed Stator Pole Sr Motor

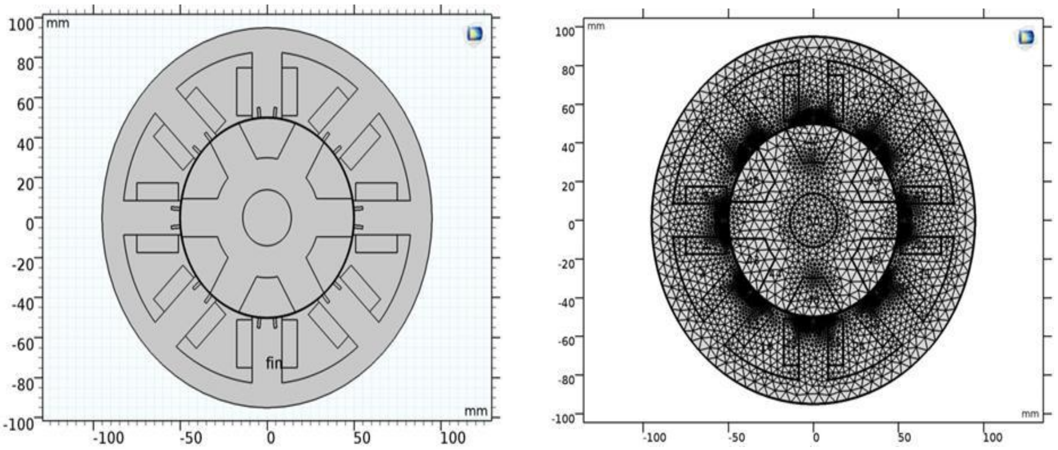

Fig 8: Design & Meshing of Multi-Teethed Stator Pole Geometry

3.5 Effect of Air Gap Dimensions on SR Motor Performance (Case-II)

In this instance, we talked about how the stator pole's air gap dimensions affect the performance of the SR motor. We discovered by Case-I that the torque performance is significantly better than the original design during the alignment of the stator and rotor poles.

In this instance, motor performance will be examined in relation to variations in the stator teeth air gap dimensions. First, we varied the air gap's width (w mm) while holding all other variables constant and analysing the motor performance of both designs (multi-toothed and teethed). Next, we varied the air gap's depth (d mm).

IV. RESULTS AND ANALYSIS

The prime objective of the research is to improve performance and efficiency of SR motor. The mathematical model is first formulated with different dimension parameter as per the requirement. In this chapter the simulation model is under test for getting response plot of different quantities. The result then is compared with previous SR motor. A comparison is carried out in multiple contexts such as inductance, magnetic flux, torque, mutual inductance and mutual flux of suggested model for industrial application. A detail study is presented in the chapter based on facts and data in tabular for comparison and different simulation plot is analyzed of required quantities.

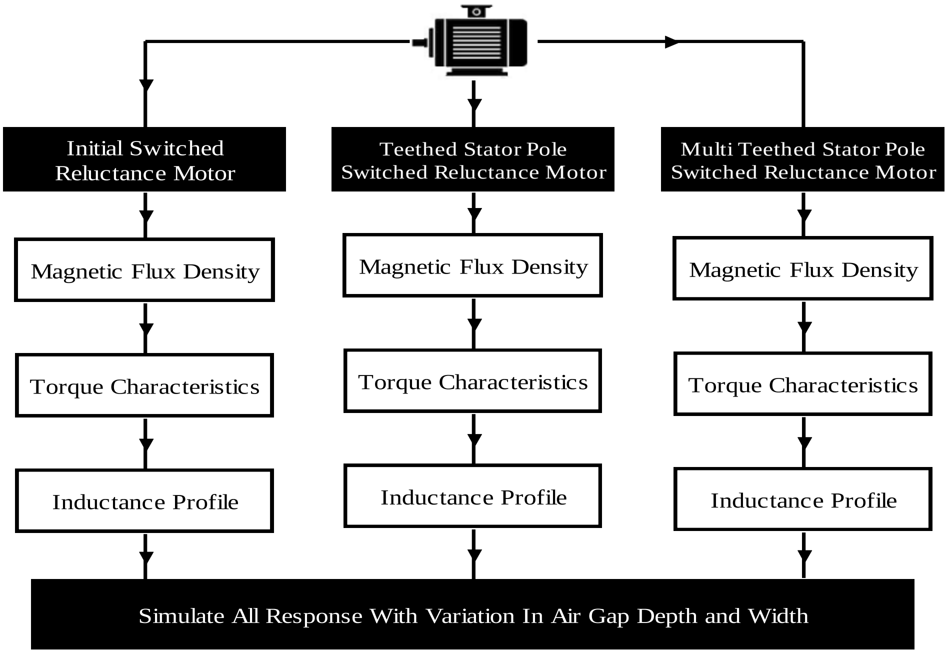

Fig 9: Test Simulation Strategy for Different SR Motors

4.1 Preparatory Switched Reluctance Motor

First I discussed about the design of the Preparatory SR Motor and the performance of the same at different condition. Torque and magnetic flux intensity is needed to consider for detailed study. Consecutive Fig. 9 depicts the above mentioned parameter in visualized format.

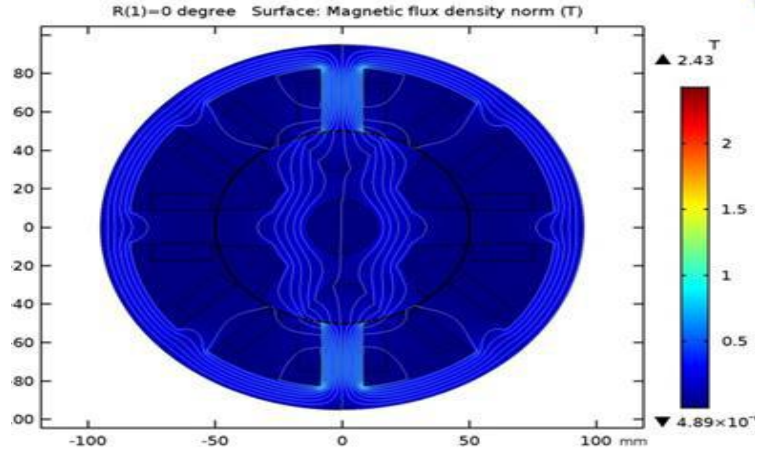

Fig 10: Magnetic Flux Density in Air Gap at 0^0 Rotor Position

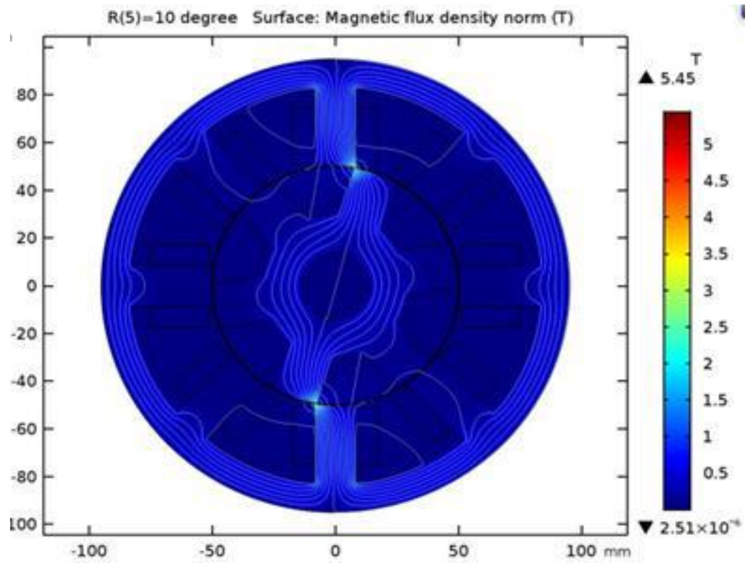

Fig 11: Magnetic Flux Density in Air Gap at10^0 Rotor Position

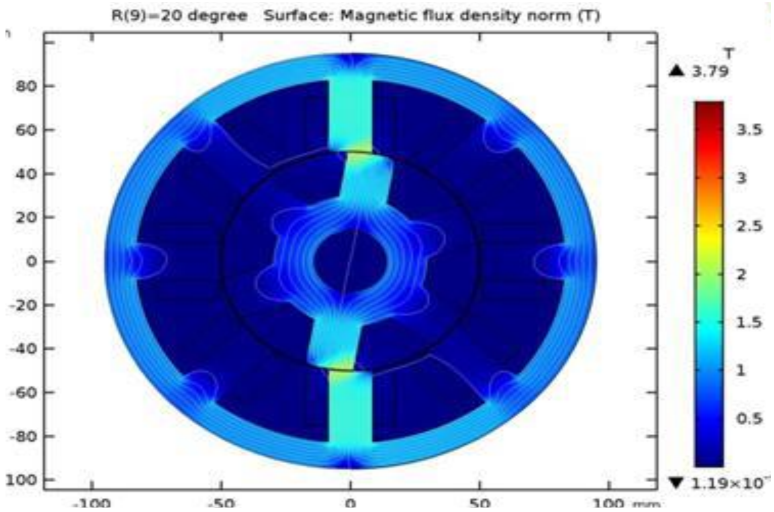

Fig 12: Magnetic Flux Density at 200 Rotor Position

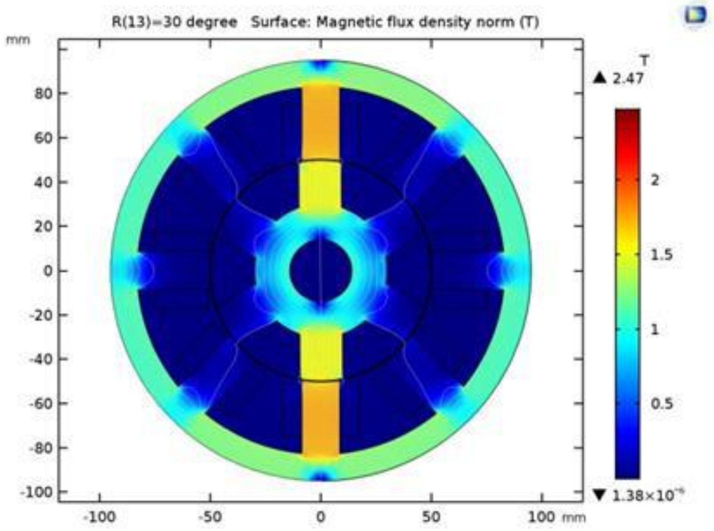

Fig 13: Magnetic Flux Density at 30^0Rotor Position

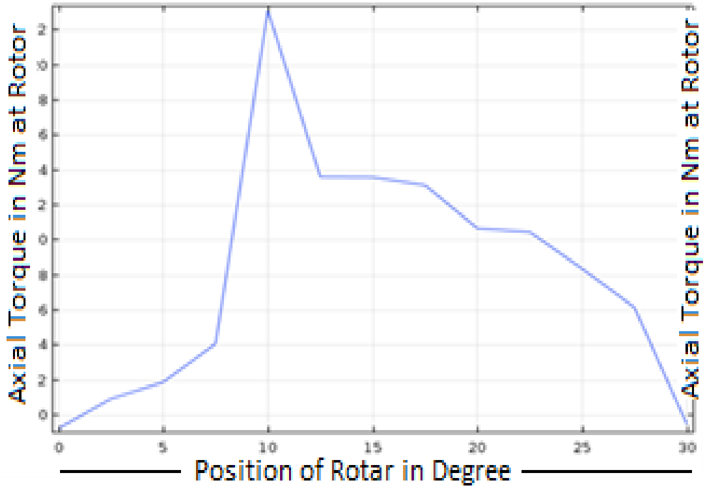

Fig 15: Torque Characteristics with Rotor Position

Color scale shows magnetic flux density norm in tesla. A characteristic between quantities axial torque and position of rotor is depicted in the Fig. 15. As the rotor changes its position there will a corresponding change in the axial torque exerted on the rotor of the motor. The change in the axial torque is depends upon the position of rotor. At 0^0 there is no torque on the rotor, means when the poles in the rotor is out of phase axial torque is zero. Then at later stage, torque is starts to build its tempo and became maximum at 10^0. At his position the axial torque in amount is 23.33N-m, which is maximum magnitude. After this position again axial torque starts to decreases and attained 0^0 at 30^0. Magnetic flux density is shown in colored graph in the response plot of axial torque and rotor position

Table 1: Self and Mutual Inductance Values at Different Rotor Position of Multi-Teethed Stator Pole SR Motor

No.	Rotor position in degree	Self-Inductance of phase A (L_a) in H	Mutual Inductance in phase B (M_{ba}) in H	MutualInductance in phase C (M_{ca}) in H	Mutual Inductance in phase D (M_{da}) in H
1	0	0.0492	0.0026	0.0000009	-0.00269
2	5	0.0541	0.0018	0.00027	-0.00399
3	10	0.0724	0.0016	0.00048	-0.00593
4	15	0.0993	0.0019	0.00055	-0.0089

5	20	0.1262	0.0028	0.00074	-0.0086
6	25	0.1414	0.0053	0.00039	-0.0092
7	30	0.1450	0.0081	-0.00004	-0.0077
8	35	0.1395	0.0093	-0.00057	-0.0044
9	40	0.1217	0.0089	-0.0008	-0.0026
10	45	0.0932	0.0084	-0.0005	-0.0018
11	50	0.0677	0.0054	-0.00045	-0.0016
12	55	0.0527	0.0036	-0.0002	-0.0020
13	60	0.0505	0.0026	0.00005	-0.0029

Table 2: Self and Mutual Flux Values at Different Rotor Position of Multi-Teethed Stator Pole SR Motor

No.	Rotor position in degree	Self-flux of phase A (F_a) in Wb	Mutual- flux in phase B (F_{ba}) in Wb	Mutual- flux in phase C (F_{ca}) in F	Mutual- flux in phase D (F_{da}) in Wb
1	0	0.637	0.0350	0.000001	-0.034
2	5	0.7033	0.02429	0.0035	-0.050
3	10	0.9412	0.0217	0.0063	-0.0772
4	15	1.2920	0.0254	0.0071	-0.1164
5	20	1.6401	0.0375	0.0097	-0.1124
6	25	1.8385	0.0698	0.0051	-0.1196
7	30	1.8863	0.1064	-0.0006	-0.1003
8	35	1.8137	0.1261	-0.0069	-0.058
9	40	1.5832	0.1157	-0.0110	-0.0342
10	45	1.2125	0.1092	-0.0071	-0.0239
11	50	0.8809	0.071	-0.0059	-0.0212
12	55	0.6861	0.047	-0.0028	-0.0272
13	60	0.6575	0.0341	-0.00068	-0.0385

When we compare the mutual- inductances values we found that mutual inductance and mutual flux values are slightly minimized by the teething of stator poles aligned position and improved at the starting and end of alignment. It is cleared that the torque profile can be improved by introducing air gap in stator poles. This type of designing improves the motor performance during alignment of stator and rotor poles, where the torque starts to decrease from 10° in initial design. The torque profile of multi-teethed stator pole SR motor gave the better performance. It also improved the flux distribution along the edges of the poles and minimizes mutual flux effect.

V. CONCLUSION

Axial torque generated in the rotor of suggested SR motor is 26.026Nm while that of the older model is 23.03Nm nearly 12% improvements in the torque. This is significant improvement in the torque of rotor of SR motor. The comparison between torques generated is presented in the table of the report.

Torque produced in the rotor of teethed stator pole SR motor is sufficiently improved up to considerable level which is a satisfactory result.

Comparative analysis of teethed poles and non-teethed poles is presented in report in tabular form.

There are two peaks in torque and speed of rotor, when poles of rotor changes the position from none aligned to aligned position, this is ripple in the rotor of SR motor. The variation in the peaks can be controlled by application of multi teeth poles in stator of the SR motor and there is not much decrease in the torque of motor. Torque is of order on nearly 25.14 Nm which is higher than normal torque which is 23.03Nm.

Ripple can further be reduced by optimizing dimension of air gap in the SR motor. Comparative analysis in context of dimension of air gap variation is presented in report.

Change in generated torque with respect to change in flux density is discussed in chapter 6 of study.

Influence of mutual inductance along with mutual flux in presented in dissertation of research.

Mutual flux direction is changes with respect to change in the phase of rotor; which ultimately depends upon connection of stator winding coil in stator poles.

Mutual flux values are same for forward and backward stator pole and vary up to 10% of self-flux values of excited phase at different rotor position. The mutual inductance is also vary up to 7% of self-inductance of excited phase with rotor movement .We got the improved performance of the motor with teethed and multi-teethed stator pole SR motor and minimize the effect of mutual coupling.

VI. FUTURE SCOPE

The research can further be extended in the following section of electrical engineering so as to meet a desired ideal SR motor for industrial application:

1. Optimization the dimension and number of teethed poles on the stator of SR motor for performance and efficiency improvement.
2. Application of pole shoe on the poles of stator of SR motor for reduction in ripple and to achieve smooth speed of motor.
3. Optimization and modification of the physical size of SR motor to get more improved performance and to manufacture the SRM.
4. Precise pole teeth air gap in between rotor pole and stator pole to meet ideal ripple free motor for better performance of SR motor
5. Geometrical modification of stator pole can be further investigated by using teethed stator pole on double cage SR motor for better performance.
6. Further research can be done to use teething of pole with pole shoe, tapered pole on stator side and non-uniform air gap between stator and rotor for motor performance improvement.

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