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Article

Design optimization and analysis of switched reluctance motor using genetic algorithm optimization technique

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Abstract: This paper presents efficiency optimization of switched reluctance motor based on genetic algorithm optimization technique. Switched reluctance motor (SRM) is considered for various applications due to its simple and robust construction. It is very essential to improve efficiency of switched reluctance motor. In this paper, optimization of 8/6 switched reluctance motor is achieved by using genetic algorithm with efficiency as its objective function. The objective of the paper is to identify the best switched reluctance motor design that provides better efficiency to satisfy the unique requirements of various applications. Using finite element analysis, a design validation of motor and characterization was made. It is analyzed that analytical results and simulation results are very close which establishes correctness of designs. The optimization result shows that the newly developed SRM design achieved better efficiency. The efficiency is increased from 82.75 % to 86.19 % with minor increase in weight. Improvement in efficiency can lead to lower energy usage, longer motor life span, and better performance.

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1. Introduction

The electric motor market has undergone significant change over the past few years in a number of areas, including its economy, availability of electricity & increasing prices, energy-efficiency policies, and its structures with company mergers contributing to a more global market. All of these changes have pushed the market towards more energy-efficient electric motors [1]. As a result of the slow shift to renewable sources, the demand for energy, and particularly electricity, is expected to increase. To compensate for any potential increase in resilience or self-sufficiency, a substantial carbon footprint penalty may be required to operate as energy-efficiently as possible as a result [2]. Many factors influence electric motor efficiency, including machine type, topology and geometry, control approach, material and manufacturing technique, and cooling conditions [3]. Permanent magnet brushless motors are widely used in commercial and

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residential locations. Permanent magnets, which are created from rare-earth elements, are what these motors rely on. Extraction and refinement of rare-earth elements are expensive, have a finite supply, and have an adverse effect on the environment. Furthermore, the performance of motors in severe conditions is compromised by permanent magnets' sensitivity to high temperatures. Consequently, there is a growing demand to create high-performance motors without rare earth elements for a variety of applications [4].

Switched reluctance motors have garnered interest in industrial, domestic and electric vehicle applications due to its rare-earth magnet free construction. Switched reluctance motor is a doubly salient machine because it uses a technology that involves the stator and rotor having silent poles [5]. The switching reluctance motor's simple & robust construction and fault-tolerant operation are its main advantages. However, there is one drawback called high torque ripple is seriously preventing this motor from finding important industrial uses. One of the main issues with this motor is the generation of acoustic noise [6]. Switched reluctance motor is of the interest of researchers and contribution of researchers is available in archival literature. The authors used analytical techniques to research the design of SRM [7–9]. These papers offer the analytical foundation needed to swiftly arrive at an initial design without resorting to significant finite-element analysis (FEA). Design strategies based on FEA techniques have been discussed in [10–12]. An SRM with auxiliary windings and PMs on the stator yoke was reported by Hasegawa et al., and the results demonstrate that the motor's torque and efficiency have enhanced [13]. However, some flaws, such a low power density and a strong torque ripple, continue to prevent its full utilization. It makes sense to improve the motor structure to fulfill the needs of various applications [14]. Power density of 25 HP, 240 V SRM is increased by 13.97% with the optimization of stator pole arc, rotor pole arc, rotor diameter and stack length [15]. Structure of 400 W,1455 rpm, 18/12 SRM is optimized based on ant-lion optimization (ALO) technique and observed reduction in torque ripple [16]. The stator and rotor pole arc angles are optimized to obtain the 5 kW, 4-phase, 1000 rpm, 240 V in-wheel SRM with high torque, low losses, and high torque density. The optimal stator and rotor pole arc angles are 22° and 23° respectively [17].

High efficiency, high torque density, low torque ripple, low cost and peak over load capacity are important performance parameters of switched reluctance motors. This paper elaborates efficiency optimization of 8/6 switched reluctance motor using genetic algorithm optimization technique. Initially a Computer Aided Design (CAD) based model is developed and validated using Finite Element Analysis (FEA) simulation and modeling technique. This initial CAD SRM is optimized by creating an objective function specific to efficiency. The optimized model shows better efficiency than the initial CAD SRM. The efficiency of the switched reluctance motor is enhanced without change in topology, materials, or other manufacturing complications, demonstrating the novelty of the suggested approach. The proposed technique is practically implementable and viable. Section 2 explains the design of switched reluctance motor and its validation with finite element analysis. Genetic Algorithm technique for efficiency optimization is discussed in section 3. Section 4 presents simulation and results. Entire work is concluded in section 5.

2. Design of SRM

Switched reluctance motor design is a procedure that is equivalent to other machine designs, in which the designer must make specific assumptions based on the rating switched reluctance motor, followed by calculation of stator main dimensions, stator design, stator winding design, rotor design. Various design variables like magnetic loading, electric loading, aspect ratio, current density, core flux density, space factor, winding factor, air-gap length etc. are assumed considering application requirements, materials availability and techno-commercial aspects. Subsequently based on the losses sustained by the machine, performance is determined and later on analyzed in electromagnetic motor design & analysis software [14, 18]. Four phase 8/6 SRM of 5 HP, 1500 rpm is designed based on following design equations.

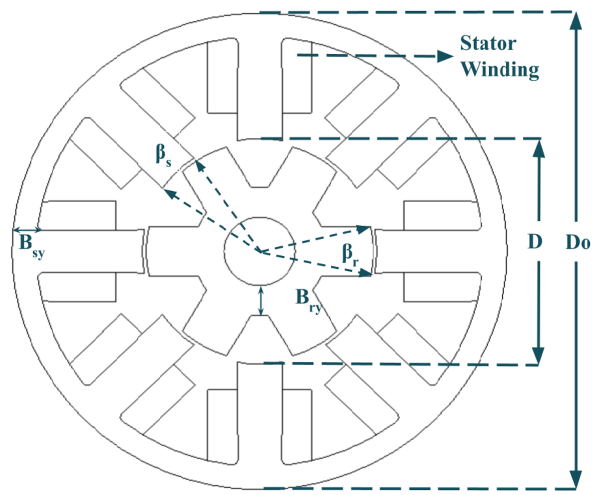

Figure 1. Parameters of SRM.

The four key steps of the switched reluctance motor design are listed below:

1. Main dimension calculations
2. Stator design
3. Rotor design
4. Performance assessment

Stator bore diameter (D) and stack length (L) are the main dimensions of SRM calculated from the following equations:

$$P_d = K_e K_d K_2 B A_s D^2 L K_3 \omega \tag{1}$$

$$T = K_e K_d K_2 B A_s D^2 L K_3 \tag{2}$$

where T - torque (N.m.), K_d - duty cycle, A_s - electrical loading (A/m), D - bore diameter (mm), L - stack length (m), K_2 - operating cycle, K_3 - constant ($\pi/4$), B - magnetic loading (T), ω - speed (rps).

Following equations are presented for winding design of SRM:

$$T_{ph} = \frac{A_s \pi D}{2m I_{rms}} \tag{3}$$

$$R_{ph} = \frac{\delta l_{mt} T_{ph}}{A_c} \tag{4}$$

where R_{ph} - resistance per phase, δ - specific resistance, l_{mt} - length per mean turn, T_{ph} - turns per phase, I_{rms} - rms current, m - number of phases.

Stator conductor size can be calculated from phase current and assumed current density. The recommended range of current density is 4 A/mm^2 to 10 A/mm^2 [19]. Winding weight, i.e., copper weight, can be calculated from the below-mentioned equation where ρ_{CU} is the mass density of copper and A_c is the area of the conductor:

$$\text{Winding}_{weight} = A_c l_{mt} T_{ph} m \rho_{CU} \tag{5}$$

Stator pole, rotor pole, stator core, and rotor core are the various sections of the SRM core having certain geometrical dimensions. Based on geometrical dimensions and mass density of core materials, stator pole weight (SP_{weight}), rotor pole weight (RP_{weight}), stator core weight (SC_{weight}), and rotor core weight (RC_{weight}) are calculated from the following equations:

$$SP_{weight} = N_s H_s W_{sp} L \rho_{M43} \tag{6}$$

$$RP_{weight} = N_r W_{rp} H_r L \rho_{M43} \tag{7}$$

$$SC_{weight} = \pi L \left(\frac{D_o^2}{4} - \frac{(D_o - 2B_{sy})^2}{4} \right) \rho_{M43} \tag{8}$$

$$RC_{weight} = L\pi \left(\frac{(D_r - 2H_r)^2}{4} - \frac{(D_{sh})^2}{4} \right) \rho_{M43} \tag{9}$$

Where ρ_{M43} - the mass density of M43 core material, N_s - number of stator poles, N_r - number of rotor poles, H_s - height of stator pole, W_{sp} - width of stator pole, W_{rp} - width of rotor pole, H_r - height of rotor pole, B_{sy} - width of stator yoke, D_r - diameter of rotor, D_{sh} - shaft diameter, and others are respective geometrical dimensions.

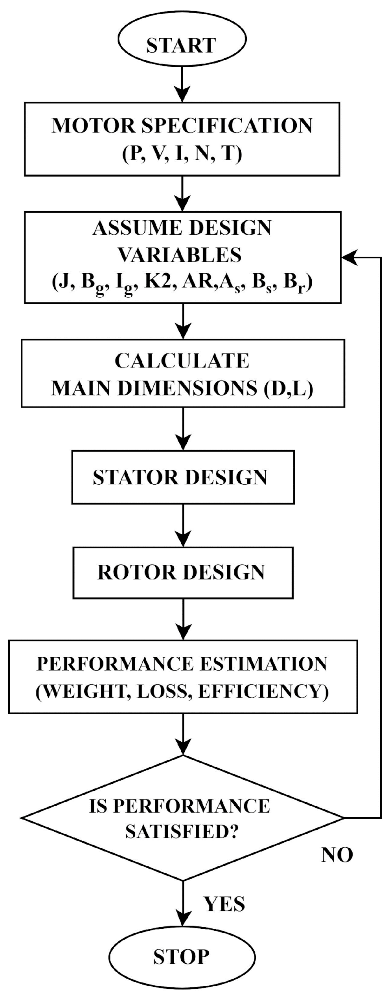

Figure 2. SRM design flowchart.

Copper losses (P_{cu}) and core losses (P_{core}) are calculated from the following equations:

$$P_{cu} = mI_{rms}^2 R_{ph} \tag{10}$$

$$P_{core} = \text{sp.Iron loss} \times \text{weight of respective section} \tag{11}$$

Windage loss, stray loss, and frictional loss are assumed to be 1% of the total output power.

$$\text{Total Loss } (P_{loss}) = P_{cu} + P_{core} + P_{windage} + P_{stray} + P_{friction} \tag{12}$$

$$\begin{aligned} P_{loss} = &\left(mI_{rms}^2 R_{ph}\right) + \left(\text{sp.Iron loss} \times H_s W_{sp} L \rho_{M43}\right) + \left(\text{sp.Iron loss} \times N_r W_{rp} H_r L \rho_{M43}\right) \\ &+ \left(\text{sp.Iron loss} \times \pi L \left(\frac{D_o^2}{4} - \frac{(D_o - 2B_{sy})^2}{4}\right) \rho_{M43}\right) \\ &+ \left(\text{sp.Iron loss} \times \pi L \left(\frac{(D_r - 2H_r)^2}{4} - \frac{(D_{sh})^2}{4}\right) \rho_{M43}\right) \\ &+ P_{windage} + P_{stray} + P_{friction} \end{aligned} \tag{13}$$

The efficiency is calculated by using:

$$\eta = \frac{P_o}{P_o + P_{loss}} \tag{14}$$

where P_o is the output power and η is the efficiency.

$$F(x) = \eta \tag{15}$$

Using (15) as an objective function and a CAD algorithm, the initial design is optimized to obtain a more efficient model.

Computer aided design (CAD) algorithm developed as per flow chart shown in Figure 2 and design of SRM has been carried out. Table 1 illustrates the design details of 5 HP SRM.

Table 1. Design information of initially designed motor.

Design parameter	Value	Unit
Stator bore dia.	119.41	mm
Stack length	98.34	mm
Stator outer dia.	222.92	mm
Number of phases	4	-
Number of rotor poles	6	-
Stator pole arc	22	degree
Rotor pole arc	26	degree
Resistance per phase	1.55	-
Turns per phase	442	–
Material of stator and rotor stack	M49	–

It is quite essential to validate the design calculations and performance estimation. Finite element modeling and simulation has been performed to validate 5 HP switched reluctance motor design. Finite Element (FE) model has been prepared as per the calculations and appropriate materials have been assigned. Two-dimensional (2-D) simulations have been performed as motor structure is axisymmetric. FE model of switched reluctance motor is shown in Figure 3.

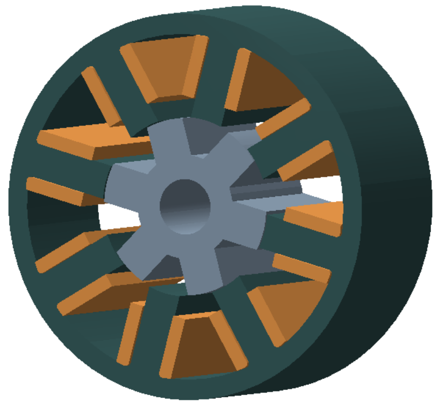

Figure 3. FE model of switched reluctance motor.

The comparison between analytical results and simulation results of initially designed SRM are shown in Table 2. Initial design is validated as it is observed that the simulation results are in proximity with the design targets.

Table 2. Comparison of Analytical and Simulation based initial design.

Performance Estimation	Analytical	Simulation
Efficiency	82.75%	83.70%
Torque	23.75 N.m.	23.17 N.m.
Total weight	20.99 kg	20.90 kg
Stator core weight	11.67 kg	11.70 kg
Rotor core weight	3.76 kg	3.76 kg
Winding weight	5.56 kg	5.44 kg
Copper loss	524.13 W	480.0 W
Iron loss	140.98 W	142.4 W
Constant loss	111.90	111.90
Total loss	777.01 W	726.0 W

Figure 4 illustrates the torque profile of motor. Inductance variation of motor for different exciting currents is shown in figure 5. It is observed that the inductance varies significantly from aligned condition to un aligned condition.

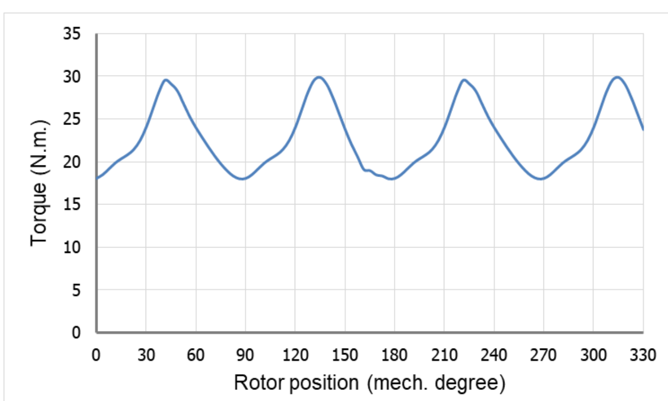

Figure 4. Torque waveform of initial design of SRM.

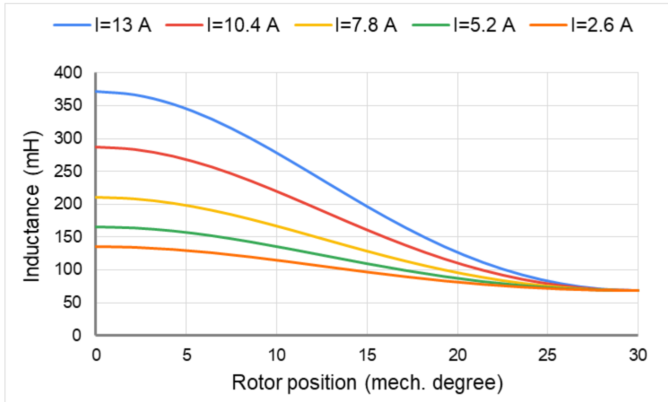

Figure 5. Inductance waveform of initial CAD SRM.

As flux density is one of the important parameters affecting motor performance, it is highly desirable to assess the flux density in various motor sections in comparison to the assumed flux density respectively.

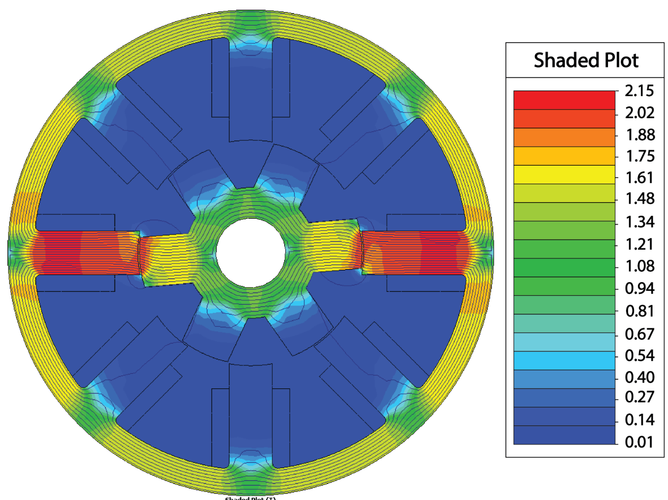

Figure 6. Field plot of initial CAD SRM.

Figure 6 shows the flux density plot of initially designed switched reluctance motor. It has been analyzed that flux density in various motor sections are very close to assumed flux density in respective section. The closeness between assumed flux density and actual flux density authenticates the motor design.

Table 3. Initial Design Variables.

Variables	Value
Aspect ratio (AR)	0.95
Air gap length (l_g)	0.7 mm
Current density (J_{max})	7 A/mm^2
Operating point (K_2)	0.75
Magnetic loading (B_g)	1.7 T
Electric loading (A_s)	25000 AT/m

3. Genetic Algorithm Optimization Technique

Maximizing or minimizing a function relative to some set, which frequently represents a range of options available in a given situation. The function enables for the comparison of various options in order to determine which is the "best." Electric motors are widely used in a variety of applications, including various applications. Lower energy consumption and improved performance are possible outcomes of optimizing motor design and control systems. Increased efficiency in electric vehicles results in long drive range, lower operating costs and longer battery life.

Genetic Algorithm (GA) is a sort of optimization algorithm. This sort of optimization methodology is taken from biological evolution and helps to address limited and unconstrained scenarios via natural selection [20, 21]. In GA, the population is a group of individuals, and the variables for optimization are known as genes. Genetic algorithm optimization is the most suitable technique in case of non-linear systems. Electric motor is non-linear system which involves magnetic circuit, electric circuit and insulation circuit hence genetic algorithm-based optimization technique is selected in this work.

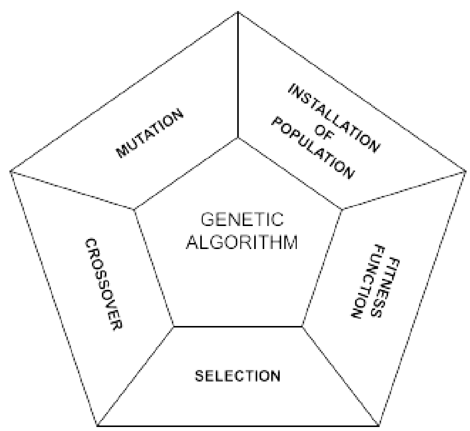

Figure 7. Representation of Genetic Algorithm.

Following are three crucial processes in genetic algorithm optimization as shown in Figure 7.

1. Selection
2. Crossover
3. Mutation

The term selection refers to the process of selecting the optimal variables for optimization that can offer favorable results. Crossover is the process of picking two sets of design variables and swapping the variables from one set to the other. Mutation is the final stage in which a single set is chosen and variables are individually flipped. After the process is completed, the final optimization variables are obtained, which are then used to calculate the motor dimensions.

4. Simulation and Results

Electric motors are used in wide range of applications hence improving their efficiency can result in significant energy conservation, better performance, and a longer motor lifespan. Enhancing the performance of electric motors can also help to lower carbon emissions and promote environmental sustainability. With these objectives, the design of switched reluctance motor is optimized.

An objective function for efficiency of SRM (equation 15) is derived. Efficiency of SRM depends on various design variables. Design variables influencing efficiency significantly are identified from parametric analysis of SRM. Following are the influential design variables with range. The range of design variables depend on material properties, availability of materials, application requirements, and manufacturing resources.

- Aspect Ratio: $0.2 \leq AR \leq 1.2$
- Air-gap length: $0.3 \leq l_g \leq 1.5$
- Current density: $3\,\mathrm{A/mm^2} \leq J_{max} \leq 10\,\mathrm{A/mm^2}$
- Operating point: $0.5 \leq K_2 \leq 1.1$
- Magnetic loading: $1.2\,\mathrm{T} \leq B_g \leq 2.4\,\mathrm{T}$
- Electric loading: $20000\,\mathrm{A/m} \leq A_s \leq 90000\,\mathrm{A/m}$

Genetic Algorithm based efficiency optimization is performed. Figure 8 illustrates variation of optimized function, i.e., efficiency, with number of generations. The simulation was carried out for 150 generations; however, optimized efficiency is converged after 76 generations.

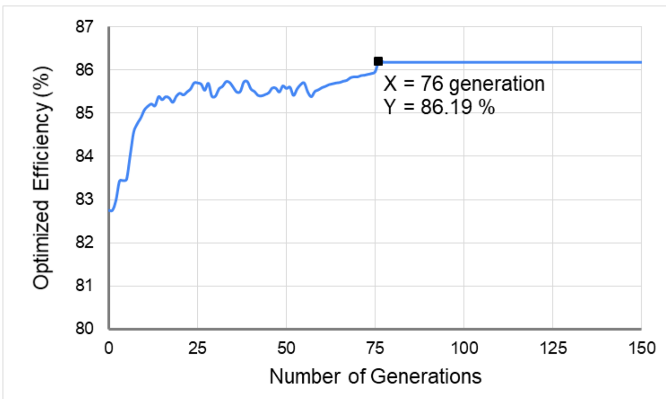

Figure 8. Variation of objective function with number of generations.

Design variables obtained after performing efficiency optimization are listed in Table 4.

Table 4. Efficiency optimized variables.

Variables	Value
Aspect ratio (AR)	0.32
Air gap length (l_g)	0.92 mm
Current density (J_{max})	4.03 A/mm^2
Operating point (K_2)	0.745
Magnetic loading (B_g)	2.0 T
Electric loading (A_s)	26468 AT/m

Using these variables, an improved SRM is designed and the dimensions of this motor are calculated. Performance of motor is determined based on calculated dimensions and material properties. Comparison of various parameters of initially designed motor and improved motor is shown in Table 5. It is analyzed that efficiency is optimized from 82. 75% to 86.19%. Weight of copper is increased by 1.54 kg hence overall cost of motor is increased by $ 12.06 considering current rate of bare bright copper wire of $ 3.55 /lb. [22].

Table 5. Comparison of CAD based SRM and optimized SRM.

Performance Estimation	Initial Design	Efficiency Optimization
Efficiency	82.75 %	86.19 %
Total weight	20.99 kg	21.61 kg
Stator core weight	11.67 kg	11.36 kg
Rotor core weight	3.76 kg	3.15 kg
Winding weight	5.56 kg	7.10 kg
Copper loss	524.13 W	297.24 W
Iron loss	140.98 W	188.15 W
Constant losses	111.90 W	111.90 W
Total loss	777.01 W	597.29 W

Analysis has also been carried out to check the effect of number of design variables on optimized function i.e. efficiency. Table 6 illustrates the effect of number of design variables on efficiency. As number of design variables increase the efficiency improves which validates the fundamental concept of optimization.

Table 6. Effect of number of design variables on efficiency optimization.

Variables	Efficiency
J_{max}, l_g	83.06%
J_{max}, l_g, A_s	83.80%
J_{max}, l_g, A_s, B_g	85.09%
$J_{max}, l_g, A_s, B_g, K_2$	85.13%
$J_{max}, l_g, A_s, B_g, K_2, AR$	86.19%

It is desirable to validate the effectiveness of proposed optimization technique and correctness of improved design. Finite element modeling and simulation is performed for design validation based on design calculations of improved motor and respective material properties. The analytically calculated dimensions are used to create model in FEA software to validate the efficiency optimized model of SRM. Appropriate materials are assigned in respective motor sections as per assumptions during CAD. Table 7 shows comparison between optimized motor design results and results obtained from simulation exercise. Closeness between analytical optimized results and simulation results validate the proposed optimization process and improved motor design.

Table 7. Comparison of optimized analytical and simulation results

Performance Estimation	Analytical Results	Simulation Results
Efficiency	86.19 %	86.52 %
Torque	23.75 N.m.	23.05 N.m.
Total weight	21.61 kg	21.79 kg
Stator core weight	11.36 kg	11.40 kg
Rotor core weight	3.152 kg	3.16 kg
Winding weight	7.10 kg	7.23 kg
Copper loss	297.24 W	326.0 W
Iron loss	188.15 W	142.99 W
Constant losses	111.90 W	111.90 W
Total loss	597.29 W	580.89 W

Figure 9 illustrates the torque profile of efficiency optimized motor. Field plot of improved motor is shown in figure 10. It is analyzed that flux density in various motor section is in proximity with respective assumed values which validates sizing of magnetic components. Figure 11 shows the inductance variation of motor from aligned condition to the unaligned condition for different motor currents.

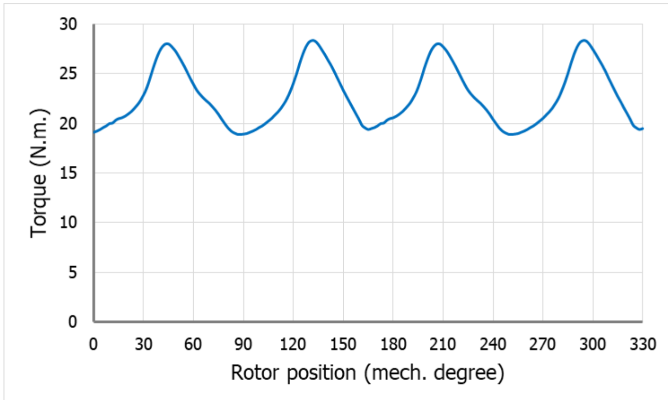

Figure 9. Torque waveform of efficiency optimized SRM.

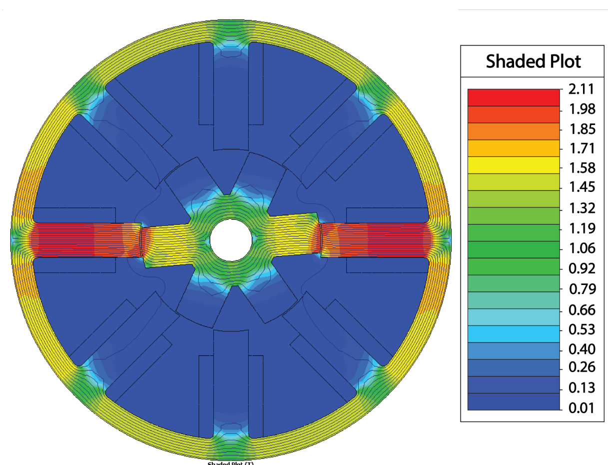

Figure 10. Field plot of efficiency optimized SRM.

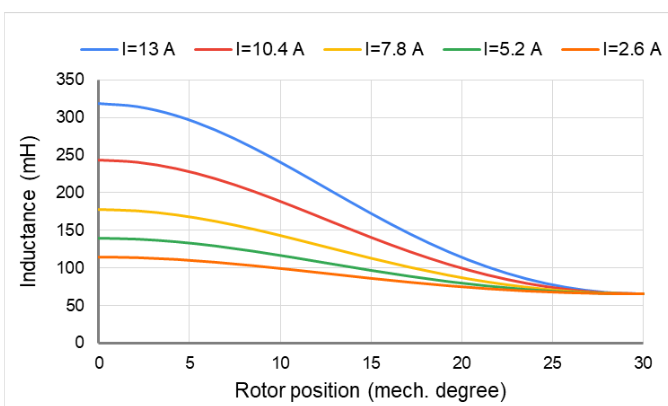

Figure 11. Inductance waveform of efficiency optimized SRM.

With an objective of performance comparison between initially designed reference motor and GA based improved motor, the bar plot is shown in figure 12. Various performance parameters of initial design are considered to be 1.0 p.u. and respective performance parameter of optimized motor is shown nearby. It is observed that the efficiency of motor is increased effectively.

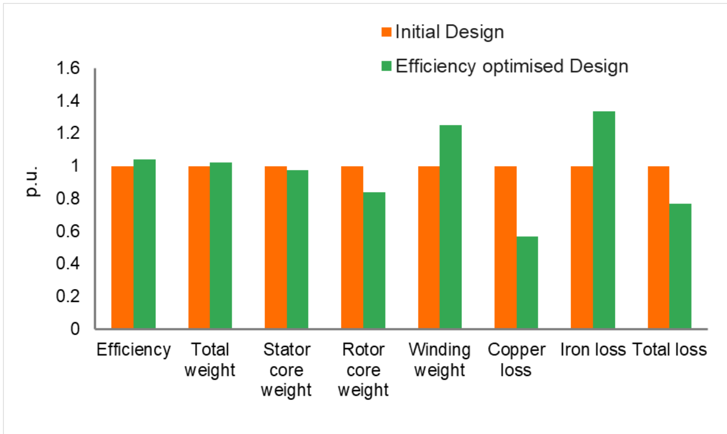

Figure 12. Relative performance of initial CAD model and efficiency optimized design.

5. Conclusions

In this paper, 8/6 Switched Reluctance Motor is optimized using genetic algorithm while creating an objective function specific to efficiency. Initially SRM is designed based on CAD and validated using Finite element analysis. The initial design has been considered as reference design for performance comparative analysis. The initial CAD design is then optimized using a genetic algorithm optimization technique and subsequently optimized design variables are obtained. Improved motor is designed with optimized design variables. Optimized motor design is validated with finite element analysis. FEA results fairly match with analytical results. The closeness between analytical results and FEA results validate the proposed technique. The result obtained from optimization shows that efficiency increased from 82.75% to 86.19%. The proposed technique can also be applied to optimize performance parameters of other type of electrical motors.

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