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Optimal Design of Switched Reluctance Motor Using Genetic Algorithm

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***Abstract*- Switched reluctance motor (SRM) has increased interest in both research and industry due to its unique characteristics. The simple structure without windings or permanent magnets on the rotor makes the motor robust, reliable, and most importantly a low manufacturing cost. SRM also provides high starting torque and high efficiency over a wide range of speeds which is strongly desired in electric vehicles application. However, these advantages of switched reluctance motors come with some challenges. Torque ripples, low power density, and temperature rise are common problems in SRMs. In this paper, multi-objective optimization of SRM design is achieved to obtain most of the SRM desired characteristics with minimization of the machine's common drawbacks. The optimization process considers twelve variables and five objective functions. Objective functions include average torque, efficiency, iron weight, torque ripples, and maximum temperature rise. The electromagnetic analysis of each candidate is performed by the finite elements method (FEA). The performance indices of SRM are calculated based on FEA analysis results by calculations that achieve both accuracy and speed. The optimization is achieved by the multi-objective genetic algorithm technique (MOGA) in which the multi-objective functions are converted to a single objective function. The efficiency map, torque profile, and dynamic simulation of the motor is provided as a verification of the optimal design. This paper mainly studies the design and optimization of SRM. The design and optimization process aims to fulfill the general requirements of electric vehicle application.**

Keywords- Switched reluctance motor, Design, Genetic algorithm, Multi-objective optimization.

I. INTRODUCTION

Switched reluctance motor (SRM) has an increasing demand recently. SRM provides several advantages which make it a strong candidate for many applications. Its simple structure doesn't require windings or permanent magnets on rotor. Moreover, the stator windings are concentrated which makes the winding process easier and hence of a low cost. The starting torque of SRM is good compared to other type of machines and close to series dc motors [1]. The efficiency of SRM cannot easily be compared to other type of machines [2]. However, comparing efficiency map of SRM with other motors shows that SRM has a wider high-efficiency area than that of induction motor and interior permanent magnet synchronous motor [3]. This increases the chances of SRM to be used in electric vehicle application.

On the other hand, SRM comes with inherent problems such as torque ripples, low power density and high temperature rise. These drawbacks must be improved to an acceptable limit. Torque ripples happen as a result of salient poles in both stator and rotor. Lots of research work is made to improve this issue [4]-[9]. Most torque ripples minimization methods suggest a certain change in SRM structure. These changes increase the complexity of SRM conventional structure. Hence, the motor loses one of its major advantages that leads to increase the manufacturing cost. In [4], it suggests that optimization of the ratios between dimensions leads to better inductance profile and hence minimum torque ripples. The profile of phase inductance is noticed to have the same features in different papers which minimize the torque in different methods. This includes the methods which depend on changing SRM structure [6], [7] and [8].

Temperature rise of SRM is analyzed in many ways such as finite elements analysis (FEA) [10]-[13], computational fluid dynamics (CFD) [14] and regression models [15]. Due to the large number of dimensions and design parameters of SRM, optimization techniques are usually used as a part of design process [17, 18].

In this paper, SRM design optimization is performed using the multi-objective genetic algorithm method (MOGA). Several objective functions are added with a weight given to each of them to be one objective function. These objective functions include average torque, efficiency, iron weight, torque ripples and maximum temperature rise. Objective functions are calculated with the help of finite element analysis (FEA). The optimization variables consider the dimensions of lamination, axial length and current density in such a way to give a wider search area for the optimization program. Hence, the program has a better opportunity to achieve all optimization objectives. SRM model in this paper depends on inductance values extracted from FEA analysis. These values are stored in table with the corresponding phase current and position. For each phase current and position values the inductance value is obtained from table. Interpolation is used in the case if current or position values are not available in the table.

Calculation methods of objective functions are discussed in next section to show the goals of optimization process. After that, optimization method is demonstrated to show how objectives are optimized. Finally, electric vehicle requirements are discussed with the results of optimization process and verification of optimal design.

II. OBJECTIVE FUNCTIONS CALCULATION METHODS

A. *Average torque*

For SRM, average torque is calculated from energy loop. As the phase current rises to a peak value then return to zero again the position of rotor pole also changed from unaligned to aligned position (in other words performing one stroke). Hence, the change of phase energy state between the aligned and unaligned positions. Average torque is calculated with the knowledge of flux linkage (λ) vs. current (i) characteristics per phase as follows:

$$T_{av} = \frac{W P_s P_r}{4\,\pi} \ , N.m \tag{1}$$

$$W = W_{aligned} - W_{unaligned} \tag{2}$$

Where P_s, P_r are the stator, rotor poles number respectively. $W_{aligned}$ and $W_{unaligned}$ are the areas under $\lambda - i$ curves at the aligned position and unaligned position respectively. W is the area of energy loop between two $\lambda - i$ curves and calculated as in [1].

To calculate average torque, numerical integration is performed on flux linkage $\lambda - i$ curve for both aligned and unaligned positions. In this way it is assumed that phase current is constant at its peak value. Usually this isn't what happens in practical operation of SRM. However, if the used control could keep the phase current constant at its peak value from unaligned to aligned positions, the highest average torque is taken from the SRM. In other words, the motor works with its full capacity. Hence, the value calculated here indicates the highest torque can SRM provide.

B. Efficiency

The Calculation of switched reluctance motor (SRM) efficiency depends on knowledge of copper losses and core losses. SRM core losses calculation can't be made with straight forward equations such as Steinmetz's equation. Since the flux wave-forms are non-sinusoidal and different in each sector of SRM iron structure. In 6/4 SRM, there are 6 different sectors which means that 6 different flux wave-forms must be obtained in order to calculate eddy current losses. The hysteresis loss which is the second type of core losses is also difficult to calculate. Moreover, core losses change with the type of control used.

In this paper the calculation methods of copper losses, core losses and efficiency are made as in [20]. The following equations summarize these calculations.

$$\eta = \frac{\omega T_{av}}{\omega T_{av} + losses} \tag{3}$$

$$P_{loss} = P_{cu} + P_{hys} + P_{ed} \tag{4}$$

$$P_{cu} = I_p^2 R_{ph} \tag{5}$$

$$P_e = \frac{e^2}{4 k_{cir} \rho_{fe} \delta} \frac{1}{T} \int \left(\frac{\partial B}{\partial t}\right)^2 dt \, , \qquad \frac{W}{kg} \tag{6}$$

Where, e is the sheet thickness in meter, k_{cir} is a constant $1 < k_{cir} < 3$ introduced to account for the fact that paths in the interior of the lamination will have smaller emfs than those near the surface. ρ_{fe} is the electrical resistivity of the ferromagnetic material (in Ωm) and δ is the density of the ferromagnetic material (in kg/m^3).

Copper losses are calculated by (5). Eddy current losses are calculated as in (6) after obtaining the flux wave-forms for all SRM sectors. Hysteresis losses calculation is more complex. It is calculated for each sector independently based on its hysteresis loop as detailed in [20].

C. Torque ripples

Torque ripples may be defined as the fluctuations in developed torque's value assuming loading conditions are unchanged. Torque ripples are undesired for all types of electrical motors. However, it is a minor problem for most of types of electrical machines and usually refers to it with the name "cogging torque". For SRM, torque ripples problem is a major concern since the developed torque itself is produced by exaggerating the cogging torque as mentioned in [2].

Torque ripples may be expressed as in (7). Wherein, the difference between maximum (T_{max}) and minimum torque (T_{min}) values is considered as a percentage of the maximum torque. To obtain these values, FEA-based dynamic model of SRM is used. In this model, square (ideal) current wave-forms are assumed. The on and off switching angles per phase are considered to be fully unaligned to fully aligned positions. These considerations and assumptions guarantee the worst-case scenario. Hence, it is expected than the real value of torque ripples would be less than calculated.

$$T_r = \frac{T_{max} - T_{min}}{T_{max}} \times 100 \qquad , \% \tag{7}$$

D. Temperature rise

Temperature rise of any electrical machine differs from point to point inside of that machine. This is a result of unequal losses distribution in the core of machine and also in the windings. Usually, temperature rise is considered at the point of highest temperature value in the machine. This point is usually located in the mid-point of the windings closer to the core side.

The heat is generated by machine losses causing temperature to increase. This increase continues until it reaches a balance state between generated and dissipated heat. The dissipation of heat in SRM happens mainly by convection. Convection coefficient (h) in SRM may has two values one for the convection or rotor and the other for convection SRM outer surface. Convection coefficient depends on the cooling conditions of the object including airflow and ambient temperature. In [19] the airflow velocities on the outer frame of the induction motor are studied for various frame sizes. In this paper, a value of 4 m/s is considered as an average value of the airflow speed on the outer frame. Hence, this process may be expressed by (8)-(13).

$$q = hA\left(T_i - T_f\right) \tag{8}$$

$$h_{st} = 14\left(1 + 0.5\sqrt{v}\right)^3 \sqrt{\frac{T_f}{25}} \tag{9}$$

$$h_{rt} = \frac{N_u \lambda}{g} \tag{10}$$

$$N_u = 0.386 T_a^{0.5} P_r^{0.27} \tag{11}$$

$$T_a = \frac{g\omega}{u} \sqrt{\frac{g}{R}} \tag{12}$$

$$P_{ra} = u\rho \frac{C}{\lambda} \tag{13}$$

where, N_u is Nusselt number, λ is thermal conductivity of

Material, g is air gap, T_a is Taylor number, P_{ra} is Prandtl number, u is viscosity coefficient, ω is rotor speed in rad/s, R is rotor radius and C is specific heat capacity.

III. Optimization Technique and Process

Due to large number of parameters that SRM design has and the non-linear relationships they have with performance indices, optimization techniques are usually used to produce better designs [4]-[9]. In most cases, meta-heuristic techniques are used such as swarm intelligence algorithms and evolutionary algorithms for the good performance they provide [23].

In this paper Multi-objective genetic algorithm (MOGA) is used to optimize SRM design. The SRM design parameters which are included as variables in optimization process are lamination dimensions in addition to axial length as shown in Fig. 1 and Table I. It should be noted that number of poles of stator and rotor are not considered in the optimization process. Instead, they are specified in the beginning of the optimization process.

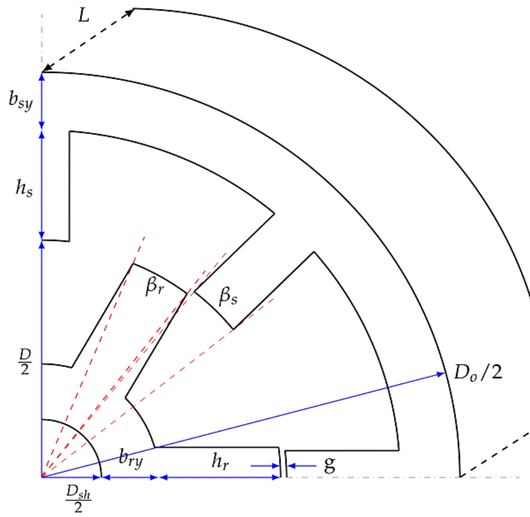

Figure 1: SRM design parameters considered in the optimization process.

Table I: SRM dimensions

Dimensions and Parameters	Unit
outer diameter, D_o	mm
shaft diameter, D_{sh}	mm
axial length, L	mm
bore diameter, D	mm
air gape length, g	mm
stator pole length, h_s	mm
rotor pole length, h_r	mm
stator back iron length, b_{sy}	mm
rotor back iron length, b_{ry}	mm
stator pole arc, β_s	rad
rotor pole arc, β_r	rad
stator poles, P_s	NA
rotor poles, P_r	NA

A. *Genetic algorithm (GA) structure*

Genetic algorithm is a search method that targets better solutions to a mathematical problem. It depends on certain calculations to give each solution a degree indicating how good it is. This search process for better solutions for a problem is referred to by "optimization" [24].

Figure 2 describes the optimization process structure using genetic algorithm. At the beginning of the optimization process, random values of solution candidates are generated. After that, they are evaluated by substituting their values in the mathematical function which represents the objective of the optimization process (hence, they are called "objective functions"). Then, the algorithm selects the best solutions based on the criteria specified in it. In other words, it selects the solution which results in achieving an increase or a decrease in the objective function's value. After the selection of the best solutions is complete, the production of the new generation of solutions begins. This production of new solutions is achieved by interchanging the characteristics of selected best solutions. This is achieved by the "crossover" process. Crossover is frequently followed by the "mutation" which is a random change in a part of new generation solutions values. This change is necessary to achieve search diversity as will come later. Finally, the optimization process must end when the desired values of the objective function are obtained or if no progress is achieved for a relatively large number of generations.

The design variables which are considered in the optimization are limited by the values shown in Table II. The determination of such values is much easier than the design of switched reluctance motor. Hence, the dependence on designer experience is greatly reduced. All variables in Table II may be considered in the optimization process except when the maximum and minimum values are equal. In this paper, the shaft diameter "D_{sh}" and the air gap "g" are excluded from the optimization. Hence, their maximum and minimum values were set equal.

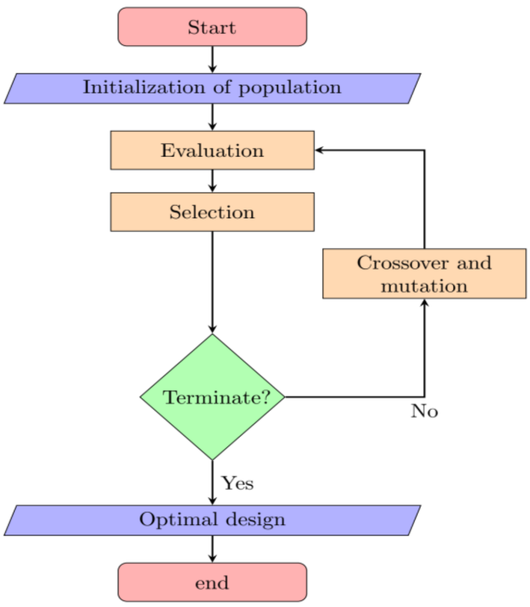

Figure 2 : Optimization process flowchart

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Table II: Limits of variables

Dimension	Min	Max	Unit
D_o	100	250	mm
D_{sh}	24	24	mm
L	50	180	mm
D	44	210	mm
g	0.5	0.5	mm
h_s	5	100	mm
h_r	5	50	mm
b_{sy}	10	40	mm
b_{ry}	5	40	mm
β_s	25.5	36	degree
β_r	25.5	43.2	degree
J	1	15	A/mm2

B. Multi-objective genetic algorithm (MOGA)

Multi objective optimization can be made in two basic ways using genetic algorithm. The first method is to transform the multi-objective optimization problem into single objective problem using weights for objective functions as follows:

$$f_{total} = w_1 f_1 + w_2 f_2 + w_3 f_3 + \cdots + w_n f_n \quad (14)$$

$$\sum_{i=1}^{n} |w_i| = 1 \quad (15)$$

In this paper, five objective functions are considered in optimization process. This includes average torque, efficiency, iron weight, torque ripples and maximum (hotspot) temperature. The objective of optimization process is to maximize average torque and efficiency and minimize iron weight, torque ripples and maximum (hotspot) temperature. The objective function is expressed by the following equation:

$$f_{total} = 0.25\,T_{av} + 0.25\eta - 0.05W_{ir} - 0.225T_r - 0.225T_{HS} \quad (16)$$

where T_{av} is the average torque in N.m., W_{ir} is the weight of iron in kg, η is the efficiency, T_r is the torque ripple and T_{HS} is the hotspot temperature in o C.

Since the units of the objective functions are different, their values must be changed to be per unit. Otherwise, false search direction is followed and the weights of objective functions are not effective. To calculate the per unit values, reasonable base values must be chosen. For average torque, the desired average torque at the specified rated speed (1000 rpm) is 22 N.m. Hence, it is considered as a base value for average torque per unit calculation. Efficiency and torque ripples are unit-less quantities and considered with their percent values. Hence, no need for base values for them. Iron weight base value(W_{irB}) is the weight of steel which solidly fills the outer frame of the motor and given by (18) considering ρ_s to be the steel density in kg/m^3.

$$W_{irB} = \frac{\pi^2 D_o L \rho_s}{4} \quad (17)$$

Hotspot temperature base value of $400^{o}C$ is considered. This value is the maximum temperature that any solution candidate may have. It is obtained from a former experimental run of the SRM optimization program at the same conditions. The optimization in this paper is of the float type which uses the roulette wheel selection method. The optimization parameters are shown in Table III.

Table III: Optimization parameters

N	Parameter	value
1	Maximum number of generations	300
2	Population size	30
3	Cross-over value	0.6
4	Mutation rate	0.25

IV. Results and Discussion

The desired SRM optimal design performance indices are represented in Table IV. The optimization of SRM was performed by the program which is written in Lua script on FEMM4.2 free package software. The progress of the optimization program is shown in Fig. 3. The elite solution is developed with generations until it reaches its maximum (optimum) value. It should be noted that the value of the objective function itself is not a matter of concern as long as the development of the solutions continuous. In Fig.4, the values of characteristics through optimization process are shown. The optimal solution was reached after 60 generations. However, the program continued to guarantee that it is not a local optimum solution. Base values are assigned for the values of characteristics in order to make the total objective function correctly balanced.

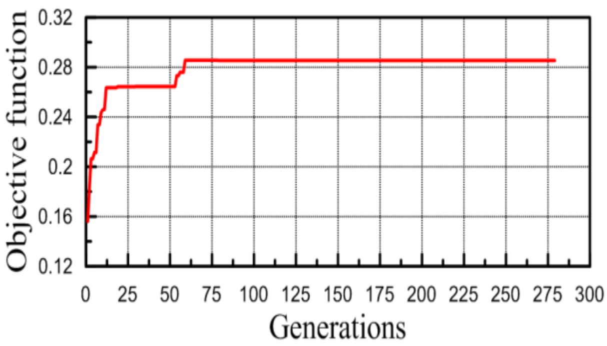

Figure 3: Total objective function's value of the optimal design with generations.

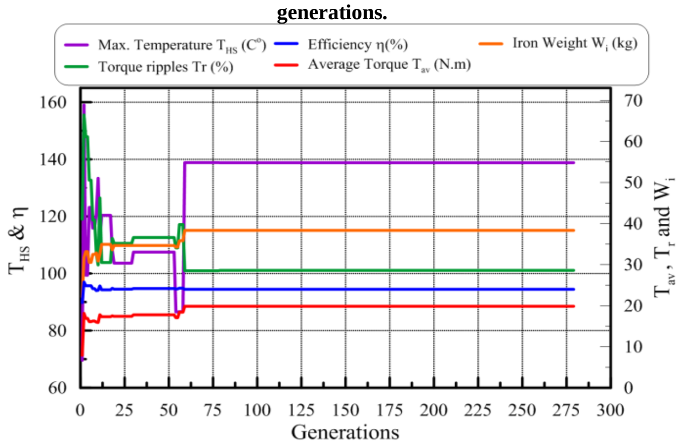

Figure 4: Characteristics values of the optimal design with generations.

Fig. 5- Fig. 9 show the values of characteristics for all design candidates through the optimization process. It can be seen that none of them goes greater than the base values which was specified for them. This shows the validation of the base values. However, some torque ripple values have values greater than 100% Fig. 8. This means that the associate design candidate has a very bad torque ripple that the value of the developed torque drops to be <0. The optimal SRM design is obtained with the characteristics shown in Table V. The characteristics of the optimal design are within the desired characteristics rages shown in Table IV.

Table IV: Targeted SRM design characteristics

N	Characteristic	target
1	Rated power	≥ 2kw
2	Rated Speed	= 1000 rpm
3	Average torque	≥ 19 Nm
4	Efficiency	≥ 90 %
5	Torque ripple	< 35%
6	Hot-spot temperature	$< 140^{o}C$
7	Iron weight	Least possible

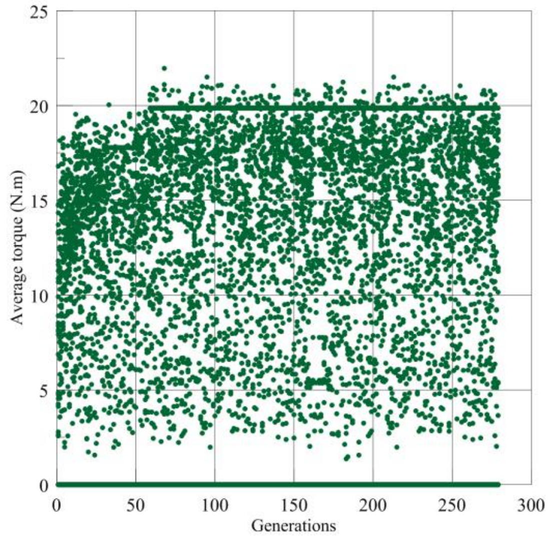

Figure 5: Average torque of all design candidates.

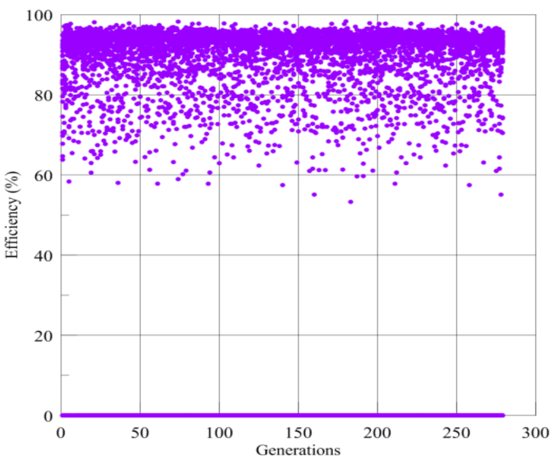

Figure 6: Efficiency of all design candidates.

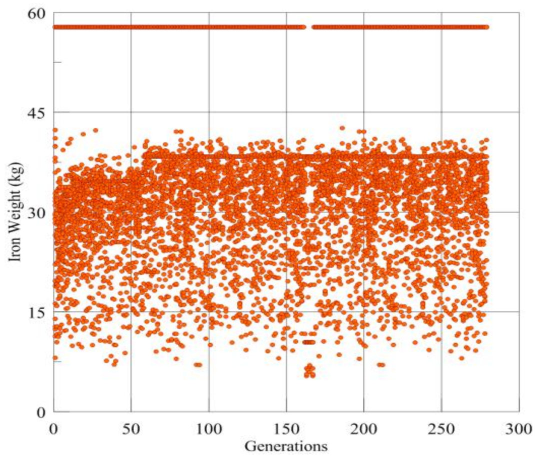

Figure 7: Iron weight of all design candidates.

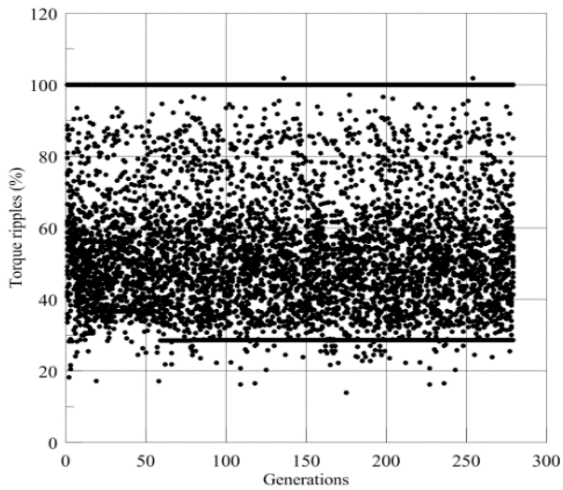

Figure 8: Torque ripples of all design candidates.

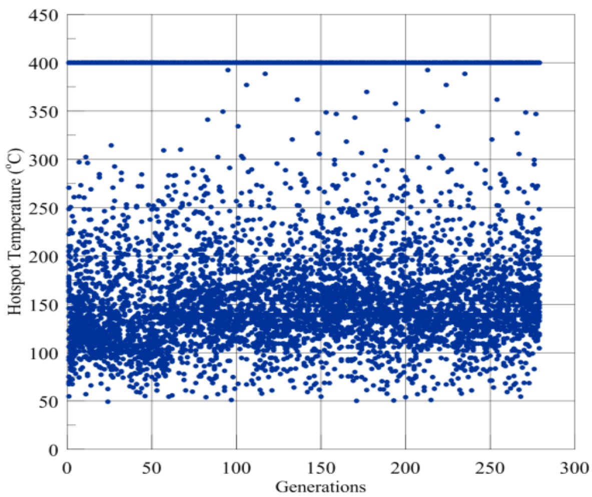

Figure 3: Hot-spot temperature of all design candidates.

The design parameters are shown in Table VI. It can be seen that their values are within the limits specified for the program in Table II. It can be seen that the difference between aligned and unaligned inductance values is great enough to achieve the required average torque mechanical forms. Fig. 12 shows the flux density inside the SRM for the aligned positions at the maximum phase current.

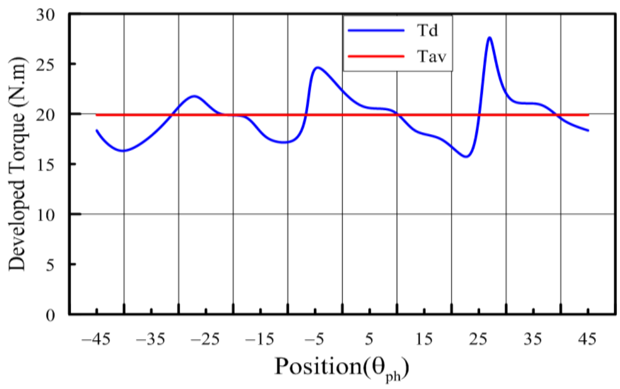

Figure 4: Developed torque with the position of rotor.

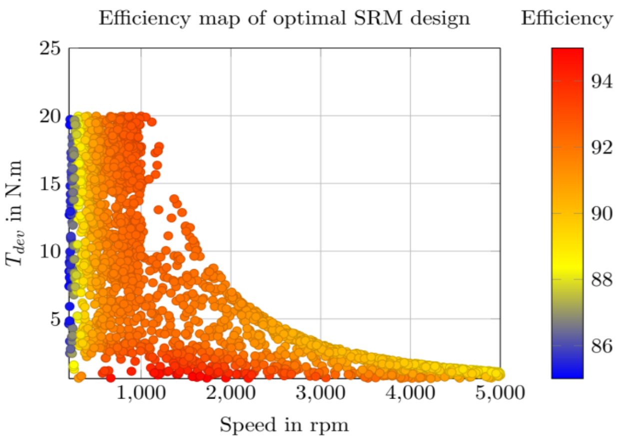

Figure 5: Efficiency map of the optimal design.

The flux density shouldn't be greater than 1.6 which was the value of stator pole flux density that SRM designed to operate at. The efficiency map for optimal SRM is shown in Fig. 11. Around the 1000 rpm the maximum value of torque is achieved. The efficiency values are calculated for speeds values up to 10000 rpm and for various values of load torque within 20 N.m.

Developed torque is shown in Fig. 10. The values of developed torque for different positions are obtained from dynamic simulation program with the help of FEA analysis. It can be notice that the average torque value matches the calculated value. Torque ripples which shown represents the worst case scenario. Wherein, each phase operates from fully unaligned to fully aligned positions. Moreover, torque ripples cab be reduced using a convenient control technique.

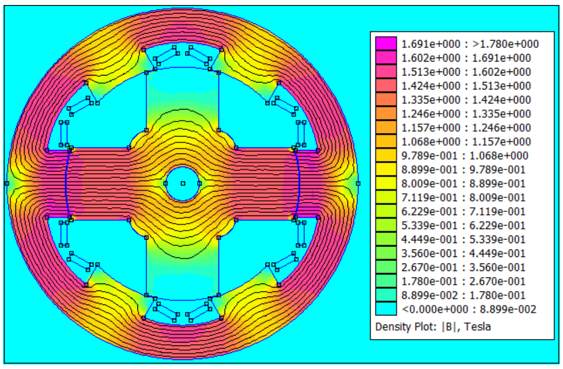

Figure 12: Flux distribution inside the optimal SRM in aligned position.

Table V: Characteristics of optimal design

Characteristic	Value	Unit
Average torque	19.9	N.m
Efficiency	94.5	%
Torque ripple	28.6	%
Hot-spot temperature	138.8	^{o}C
Iron weight	38.3	kg

Table VI: Parameters values of the optimal design

Parameter	Value	Unit
T_{ph}	288	Turns
L_a	523	mH
L_u	25.5	mH
R_{ph}	1.7	Ω
D_o	250	mm
D_{sh}	24	mm
L	142	mm
D	167.4	mm
g	0.5	mm
h_s	16	mm
h_r	41.2	mm
b_{sy}	25.2	mm
b_{ry}	30	mm
β_s	32.9	degree
β_r	35.7	degree
J	4.74	A/mm^2

V. CONCLUSIONS

In this paper, the optimization of SRM design using multi-objective genetic algorithm (MOGA) technique is discussed. The optimization process considers 12 variables in order to increase the search area and the opportunity of finding better designs. The objectives of optimization included performance indices and characteristics. This includes average torque, efficiency, iron weight, torque ripples and hotspot temperature. The results are discussed to evaluate both optimization technique and SRM optimal design. Results show the success of the optimization technique to produce better solution. The SRM optimal design is verified using FEA. The optimal SRM design characteristics are accepted as their values are within the targeted ranges.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

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