Analytical Method for Optimal design of Synchronous Reluctance Motor for Electric Scooter Application

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In recent years, synchronous reluctance motor (SynRM) has attracted the attention of researchers and well-known companies have been involved in designing and manufacturing electric motors due to its simplicity. The current study aimed to provide a comprehensive approach to design a series of SynRMs using both combined methods and finite element analysis to achieve an algorithm which is based on the similarity between flux lines and the shape of flux barriers to achieve both maximum torque and minimum torque ripple. In this paper, a SynRM is designed for a specific electric vehicle. Consequently, study cases with a different number of both flux barriers and poles, are analyzed and optimized in each case. Finally, the optimal specifications of the motors are compared in different cases and the best one is selected. Accordingly, the design parameters are identified and optimized through the Taguchi method and then, the obtained results are evaluated through finite element analysis. To achieve both maximum torque and minimum torque ripple in a range of power between 150 to 750 watts, three different number of poles with a constant number of slots (per pole per phase) at the same size for all the described motors are considered. The validity of the proposed method is confirmed through the experimental test results.

Index Terms—Flux barrier, Taguchi method, Flux lines, Torque ripple, Electric scooter.

I. INTRODUCTION

Synchronous reluctance motors (SynRM) have a simple rotor structure [1]-[2] because they require neither a squirrel cage nor permanent magnets in the rotor. Magnetic reluctance is the only factor that produces torque in the rotor according to the shape, flux barriers position, and air gap. Hence, these parameters result in the complexity of rotor design calculations. To improve the performance of the SynRM motor, the use of auxiliary magnets to achieve high torque density has attracted a lot of attention. Diverse models of rotors with a different form of permanent magnet placement have been proposed for better motor performance [3]-[5], but adding a permanent magnet will cause problems such as cogging torque, strong armature reaction, as well as difficulty in assembling the motor. Studies to reduce torque ripple in a reluctance synchronous motor can be generally divided into three categories: the first category is the research on control methods [6]-[7] and the second category whose research focuses on design parameters, especially rotor design, the idea of choosing an asymmetric stator to reduce the torque ripple is suggested in [8]. Displacing rotor poles and creating a rotor with asymmetric poles can be another approach to reduce torque ripple [9]. In the third category, the use of multi-objective optimization algorithms for the parametric design of motors with several barriers for optimal design has been performed [10]-[11]. Different methods have been suggested in the literature for rotor design; for example, designing based on magnetic equivalent circuit [12]-[15] mathematical relationships and physical concepts [16] and [17], and most recently, combining these relationships according to sensitivity analysis of the parameters involved [13], [18] and [19]. Rotor design parameters are complicated and time-consuming. Therefore, the most basic parameters with the greatest impact on the location and shape of the flux barriers are investigated in this paper to provide the simplest and the most generalizable design. According to the studies [20]-[22] carried out, three design parameters including the flux barriers insulation ratio in the q axis (defined as the ratio of the insulation layer to rotor iron thickness), the distance between the center of each barrier and the motor shaft, and the width of each barrier, have the greatest impact on the SynRM performance. Therefore, the positional arrangement of the barriers and their dimensions affects the saliency ratio and output parameters of the motor. Using these parameters, a simple and general design method is proposed in this paper to design a SynRM with different flux barriers which are based on the flux line distribution on the solid rotor.

A SynRM rotor is optimized by determining the optimization target variables and defining a range of variables affecting the objective function using the Taguchi optimization method and a limited number of finite element sensitivity analysis studies on the design parameters. The purpose of this paper is to propose the optimal design method for reluctance synchronous motor. Designing different rotor topologies in a reluctance synchronous motor requires utilizing different methods of mathematical calculations because based upon different curves, the shapes of flux barriers are mathematically defined. The equations that define these curves can be very complex.

In this paper, the shape of the magnetic flux barrier is designed by the conformal mapping method. Based on these calculations, the main parameters affecting the shape of flux barriers on the output characteristic of the motor have been recognized using the Taguchi method and sensitivity analysis, as well. Average output torque and torque ripple have been nominated as design optimization targets. The critical point is the width and position of the flux barriers along the q axis. In this regard, the effects of the number of motor poles, the number of magnetic flux barriers, the shape and the position of the flux barriers inside the rotor have been investigated on the torque characteristic of the SynRM motor. On the other hand, the end-points of the flux barriers along the d axis have a great impact on improving output torque ripple. The effect of defined parameters on motor performance has been studied by the FEM method for all design cases. The main advantage of this method is the reduction of the number of experimented finite element analysis by considering the geometric parameters that are effective in designing the shape of flux.
barriers. Additionally, the sensitivity analysis of the d axis parameters and the Taguchi optimization method on the q axis parameters, separately, prevent impossible combinations of the geometric parameters of the rotor. Finally, based on the analysis of the obtained results from the designs, the final configuration of the motor for use in the electric scooter is selected.

II. SYNRM ROTOR DESIGN

An algorithm is proposed to design the rotor in this paper according to Fig. 1. In the first step, an initial rotor is designed with the equations proposed in [18]-[21] which include: (a) estimation of the flux barrier according to flux line distribution on the solid rotor, (b) determining the width and position of flux barriers in the q axis. In the second step, the parameters affecting the output characteristics of the motor are selected, the motor is optimized to select the q axis parameters and the results are validated by the Taguchi method through finite element analysis and then both the results of the above methods are compared. In the third step, the secondary d axis parameters (endpoints of the flux barriers) that have a major impact on the torque ripple are selected. The obtained results are compared by the sensitivity analysis method and the best case is selected as the optimal rotor design. This process is repeated for different motors with the same dimensions and a different number of poles and flux barriers.

The gearbox ratio needs to be chosen so that maximum motor speed at nominal power is converted to the maximum motor speed under field weakening condition. For the selected scooter dimensions, the gearbox ratio is as follows [22]:

$$ G = \frac{\omega_{\text{Max-Motor}}}{\omega_{\text{Max-wheel}}}, G < 10 $$

(1)

Therefore, the maximum torque at low speed is given by:

$$ T_{\text{Max}} = G \frac{P_{\text{rated}}}{\omega_{\text{Max-motor}}} $$

(2)

Where $G$ is gearbox ratio and $P_{\text{rated}}$ is the power of the motor.

Firstly, to determine the torque and speed of the scooter, the required force by the scooter is calculated by the following equation:

$$ F_T = F_r + F_{ad} + F_h + F_a $$

(3)

where $F_T$ is the total driving force, $F_r$ is rolling resistance force, $F_{ad}$ is aerodynamic drag force that is related to the shape of the scooter, $F_h$ is the force to overcome the weight of the scooter and the gravity of the slope that the scooter should pass, $F_a$ is the acceleration force in the scooter which is a linear force.

FIG. 1 HERE

The forces that the scooter must overcome are as the following [23]:

$$ F_r = \mu r mg $$

(4)

$$ F_{ad} = 0.5 \rho A C_d g v^2 $$

(5)

$$ F_h = mg \sin(\phi) $$

(6)

$$ F_a = ma $$

(7)

where $\mu_r$ is rolling resistance coefficient (0.015 for the scooter tire), $m$ is vehicle portable weight (60kg), $g$ is gravity factor (9.8 m/s²), $\rho$ is the density of air (kg/m³), $A$ is the area of the front part of the scooter (0.6 m²), $C_d$ is vehicle aerodynamic coefficient (0.7), $v$ is the velocity of the vehicle (10km/h), $\phi$ is the slope of the road, and $a$ is acceleration.

FIG. 2 HERE

FIG. 3 HERE

As shown in Fig. 2 and Fig. 3, a motor with a power of 0.15 kW is chosen to move a weight of 60 kg with a maximum speed of 20 km/h on a zero slope road and similarly, a motor with a power of 0.3 kW is required on a road with a slope of 10 degrees at a maximum speed of 10 km/h. Therefore, the mechanical structure of Fig. 4 is utilized with a diverse number of poles for a certain power range (0.15kW to 0.75kW).

FIG. 4 HERE
The general specification utilized for the initial motor design along with all study cases is presented in Table I and Table II, respectively.

TABLE I HERE

TABLE II HERE

III. MATHEMATICAL APPROACH

Following the proven rules in fluid dynamics is the way to achieve the maximum flux in the d axis and to block the flux in the q axis that is the main goal of all rotor designs. This leads to increasing the saliency ratio which is defined as the ratio of the d axis inductance to the q axis inductance. To understand the matter better, the distribution of the flux lines on a simple and solid rotor without any flux barriers is shown in Fig. 5.

The best and the most effective way to block the fluid flow is to put the barriers perpendicular to the fluid path. Here, flux lines are considered as the fluid flow. Accordingly, to provide the maximum barriers to the flux lines of the q axis, the barriers along the q axis are assumed to be perpendicular. Following this method leads to different shapes of the flux barrier which depends on the insulation ratio of d and q axes, the number of flux barriers, the distance between flux barriers, and mainly end-points of the barrier flux. The barrier along the d axis should be parallel to the d axis flux lines and perpendicular to the q axis flux lines as far as possible.

According to [21], selecting the barriers along the q axis directly affects the average amount of torque, and also both the shape and the position of the barriers along the d axis have a major impact on the amount of torque ripple.

FIG. 5 HERE

A: SHAPE OF THE FLUX BARRIERS IN Rotor

Now by using the concept of simple congruent mapping in the complex analysis theory and the Zhukovski function, equation 8 can be written as the following [12] and [19]:

$$f(z) = \left( z + \frac{a}{z} \right)^2 = z^2 + 2a + \frac{a^2}{z^2}$$  \hspace{1cm} (8)

Where $Z = x + jy$ is a complex variable; by dividing the real and the imaginary parts of the function $f(z)$, the imaginary part can be written as follows:

$$2xyw^2 = v$$  \hspace{1cm} (9)

where $w$ and $v$ are real variables that can be changed to obtain different Zhukovski curves. It should be noted that the analytical solution of equation (9) can be complicated; therefore, using parametric equations is the simplest way to explain the Zhukovski curves [23] and [24].

$$x^2 + y^2 = r_d(\alpha, w, v)$$  \hspace{1cm} (10)

$$\frac{y}{x} = \tan(\alpha)$$  \hspace{1cm} (11)

Equations 10 and 11 can be integrated in equation (9), and the Zhukovski parametric equations can be expressed as follows:

$$\begin{cases} x = r_d(\alpha, w, v) \cos(\alpha) \\ y = r_d(\alpha, w, v) \sin(\alpha) \end{cases}$$  \hspace{1cm} (12)

As already mentioned, the flux lines in d and q axes are orthogonal. Therefore, all of the orthogonal curves on the d axis flux curves can be shown by the real part of $f(z)$ (equation (13)).

$$2w + x^2 - y^2 + \frac{\left(x^2 - y^2\right)w^2}{\left(x^2 + y^2\right)^2} = u$$  \hspace{1cm} (13)
Equations (3) and (4) can be integrated into equation (6) to calculate one of the parameters of equation (5) such as the radius. Hence, the orthogonal curves can be calculated according to the radius of the following equation [22] and [23].

\[ r_d = \sqrt{\frac{u - 2w + \sqrt{(2w - u)^2 - 4w^2 \left(2\alpha\right)^2}}{2\cos(2\alpha)}} \]  

(14)

According to equation (14), by which the radius is calculated, the radius has a direct and binary relation with the angle \( \alpha \), and the two parameters \( w \) and \( v \) are variables. However, the parametric equations are better than equation (2) to determine the shape of the flux barriers which should be solved numerically. Using equations of the barrier curves which the flux lines passing through and using equations (13) and (14), the flux paths in the rotor can be considered as the following equation.

\[ r(\theta) = \left(\frac{D_{shaft}}{2}\right)^p \sqrt{\frac{C + \sqrt{C^2 + 4\cdot \sin^2(p\theta)}}{2\cdot \sin(p\theta)}} \]  

(15)

Where \( p \) is the rotor number of pair of poles, \( r \) is the radius passed through the rotor center, \( \theta \) is the mechanical angle of the d axis in the polar coordinate (the cylindrical coordinate system), \( D_{shaft} \) is the motor shaft diameter and \( C \) is a constant which is a function of the points where the flux lines are passing through. According to the above equations, these curves can be represented by \( \theta(r) \) according to the following equation:

\[ \theta(r) = \frac{1}{p} \cdot \sin^{-1} \left[ \frac{\left(\frac{r}{D_{shaft}}\right)^p}{\left(\frac{D_{shaft}}{2}\right)^{2p} - 1} \right] \]  

(16)

The constant \( C \) can be calculated from equation (16) according to the angle and radius based on the following equation:

\[ c = \sqrt{\frac{\left(\frac{r}{D_{shaft}}\right)^{2p}}{\left(\frac{D_{shaft}}{2}\right)^{2p} - 1}} \]  

(17)

Equations (8) to (17) are used in the first step of the rotor design. The beginning and the end-point of each flux barrier on the q axis are calculated according to the rules given in the next section. Knowing the value of parameter \( C \) for each flux path which is the same for all of the points of the path and also having the angle or radius of the next points, the barrier shape is determined as shown in Fig. 6.

FIG. 6 HERE

B: Calculating the width of the flux along the axis q

This section pertains the calculation of the width of the flux barriers in the q axis.
FIG. 7 HERE

As it can be seen in Fig. 7, the coordinates of points $PBj$ should be specified along the q axis where $B$ refers to barriers, $j$ is the number of points in the rotor, $\delta_i$ is the opening angle of the selected ith barrier layer and $i$ is the number of flux barrier. To determine these points, the number of flux barriers and the insulation ratio should be chosen first. Insulation ratio on the q axis is defined as the ratio of flux barrier thickness along the q axis to iron thickness in rotor along the q axis, $k_{iq}$ [18], [19], and [20]. The width of the flux barriers and the iron sections along the q axis is calculated through equations shown by [21], [26]-[29]. This rule is expressed by equation (18):

$$\frac{WB_k}{WB_m} = \frac{\Delta f_k}{\Delta f_m} \sqrt{\frac{S_{bk}}{S_{bm}}}$$ \hspace{1cm} (18)

$$\Delta f_k = f_{q+1} - f_{qk}$$ \hspace{1cm} (19)

Where $k$ and $m$ denote the number of flux barriers, $\Delta f_k$ is the per-unit magneto-motive force (MMF) mean difference, and $S_{bk}$ is the length of the $k$th barrier (Fig. 8).

The main parameters which are required to design and locate the flux barriers in the rotor are as follows: (a) the distances between the flux barriers represented by ($S_i$) and (b) the thickness of the flux barriers along the q axis represented by ($WB_i$) (see Fig. 6). It is suggested in [21], [23], and [30], that if the difference of the number of stator slots per pair of poles $(ns)$ and the number of rotor slots per pair of poles $(nr)$ equals to ±4, then a more reasonable result will be achieved [29], [30]. The distances between the flux barriers, ($S_i$), is calculated by equation (20):

$$\frac{2S_1}{S_2} = \frac{f_{d1}}{f_{d2}} \frac{S_h}{S_{h+1}} = \frac{f_{d1}}{f_{d2}}$$ \hspace{1cm} (20)

Where $f_{dh}$ is the magneto-motive force along the d axis and $h=2… K$ [29].

According to Fig. 8 (b), the magneto-motive force along the d axis in each segment is equal to the mean value of magneto-motive force by that segment. Therefore, $f_{dh}$ is calculated by averaging the magneto-motive force between the two endpoints of the segment $k$th [18], [21], and [27].

FIG. 8 HERE

IV. SEQUENTIAL SUBSPACE MULTI-OBJECTIVE OPTIMIZATION OF SYNRM

After the initial rotor design, seven geometric variables are considered to be analyzed and then to design the rotor optimally. The simplified topology of the rotor is depicted in Fig. 4 where the design variables are $Yqi$ (the distance between the center of magnetic barrier along the q axis and the rotor), $WB_i$, and $k_{iq}$. Summarizing the selected parameters, there are still 7 variables involved in the design of the rotor in all cases of design. Each of the variables is evaluated at 3 equal levels. The specific values of each level such as case1 are shown in Table III.

TABLE III. HERE

All of the cases require $3^7 = 2187$ experiments for each motor, which is a considerable number; therefore, the Taguchi method is introduced to determine optimum values for the rotor variables. The orthogonal test table of L27 (3) is shown in Table IV. Having the obtained optimum point, required modifications to achieve the optimal point are applied and the results are simulated, then the values obtained from the Taguchi method are compared with these results. The optimal combination of factor levels and average torque values and torque ripple at the optimum point is calculated.

TABLE IV. HERE

Since the objective is to optimize the two results simultaneously (the maximum value for the average torque and the minimum value for the torque ripple), the analysis of variance should be used to find the optimal combination. Analysis of variance helps us to evaluate the contribution of each factor to the distribution of total responses. To this end, the sum of squares is calculated for
According to the obtained results and comparing the simulation results shows that the average torque gets increased in all of the cases, for instance, in Case 5, the average torque of the optimal design is improved by 19% and in Case 2, the torque ripple decreased by 49%. Furthermore, torques of all optimal cases are presented in Fig. 9.

To select the best case and to have a better understanding of the performance of the motors, the average torque and torque ripple of the motors in all cases are shown in Fig. 10. According to the obtained results and compromising between the results and also considering the average torque value and the torque ripple value, simultaneously, Case 2 is selected as the best one.

In addition, the torque can be generally calculated using equation (27) which is,

\[
T_{\text{avg}} = \frac{3}{2} \frac{P}{2} \left( L_d - L_q \right) \cdot I^2 \cdot \sin \left( 2\theta \right)
\]

(27)
Where $p$ is the number of rotor poles, $L_d$ is the inductance value in the d axis, $L_q$ is the inductance value along the q axis, $I$ is the stator peak current, and $\theta$ is the current angle.

**FIG. 9 HERE**

According to equation (27), the amount of torque is related to the both number of rotor poles and the difference between the d and q axes which are directly related to the both motor saliency ratio and the stator current.

**FIG. 10 HERE**

Fig. 11 shows the inductance values of the d and q axes and their difference and Fig.12 depicts the saliency ratio of all motors. Based on the presented results, the increase in the number of poles does not necessarily ensure the torque improvement because it leads to inductance difference reduction and saliency ratio, as well.

**FIG. 11 HERE**

**FIG. 12 HERE**

**VI. ELECTRICAL CHARACTERISTICS EVALUATION**

The highest inductance difference in Fig. 11 is related to case 1 and the effect of this value is large enough to affect the number of pole pairs. Furthermore, different values of the current amplitude are considered. The stator current amplitude is examined in all cases from 9 Amps to 25 Amps. The resultant torque is shown in Fig. 13.

**FIG. 13 HERE**

According to the obtained results, although by increasing the stator current, the average torque value is leveled up in all cases (see Fig.13 (a)), and the low levels of torque ripple are related to case 3 and case 6 (Fig. 13 (b)) which are four and eight poles cases, respectively (Table. II). In conclusion, by considering the average torque and the torque ripple of all the experiments obtained through the finite element method, in high values of current, the best torque with the lowest torque ripple is obtained in Case 6 which is formed of an eight-pole motor with four flux barriers. For the selected Cases 2 and 6, the torque – current – angle surfaces are shown in Fig. 14 (a) and Fig. 14 (b), respectively. In addition, the flux line distribution of two cases at 9 Amps (low power) for Case 2 and at 20 Amps (high power) for Case 6 are shown in Fig. 15 (a) and Fig. 15 (b), respectively.

**FIG. 14 HERE**

**FIG. 15 HERE**

**VII. SELECTING AN OPTIMAL DESIGN**

In this section, based on the provided results, the process of designing of the optimal rotor is presented. According to Table VI, using the proposed method, in comparison with the initial design, the average torque is increased by 19% in the eight-pole motor with three flux barriers, and the torque ripple is decreased by 20.4% in the four-pole motor with three flux barriers. Then, using the general equation of the SynRM torque, the experiment is performed at different current values, and it is shown that due to the relationships among the parameters affecting the motor torque and by changing the current in each case, the motor reaches the maximum torque with an appropriate ripple at a particular current. In this regard, six-pole motors with three flux barriers have the best performance at currents lower than 12 Amps and also at 300 watts of power, and eight-pole motors with four flux barriers have the best performance in higher currents and powers up to 750 watts.

As the result of Fig. 13 indicates, to produce the highest average torque with the lowest torque ripple at currents less than 15 A, a motor with six poles is an appropriate choice. Therefore, a motor with six poles is selected as the final design. To optimize the motor by the Taguchi method [31]- [32], the number of optimization factors and the levels of design variables are selected for the design where the control factors as well as the selected levels are shown in Table VII.

**TABLE VII. HERE**

In the next step, an appropriate orthogonal array is selected and the matrix is constructed in which recommended experiments are arranged by the Taguchi approach. By analyzing the results of the indicated tests, the appropriate levels can be determined for...
each factor. Therefore, based on this arrangement and as shown in Table VIII, 25 tests should be performed totally for five factors in five levels.

### TABLE VIII. HERE

The results obtained from the calculations for the average torque and torque ripple, shown in Fig. 16 (a), indicate that the maximum average torque is achieved by selecting \( \Delta Yq_1 \), and \( k_{\text{wp}} \) in the fourth level, \( \Delta Yq_2 \) in the second level, and \( \text{WB}_1 \) and \( \text{WB}_2 \) in the fifth level, respectively. As shown in Fig. 16 (b), it is clear that the lowest torque ripple value is obtained by selecting \( \Delta Yq_1 \), \( \Delta Yq_2 \), and \( \text{WB}_1 \) in the first level, and \( k_{\text{wp}} \) in the second level and \( \text{WB}_2 \) in the fifth level, respectively.

### FIG. 16 HERE

As can be noticed in Fig. 16 (a) and (b), to select the appropriate levels of factors, it is necessary to have an index to determine the effect of each factor on the optimization objective function. To serve this purpose, the analysis of variance has been used. Using ANOVA (analysis of variance) can be useful to determine the effect of input parameters on output results. Then, according to equations (21) to (23) the effects of the impact weight of all design variables on the desired output obtained through calculations are presented in Table IX. The selection of appropriate levels of variables is done by comparing the S/N analysis results shown in Fig. 16 and the results obtained in Table IX. Then, the optimization variables are selected to achieve the best design results for both average torque and torque ripple. Consequently, 1\(^{st}\) level of \( \Delta Yq_2 \), 4\(^{st}\) level of \( \Delta Yq_1 \) and \( k_{\text{wp}} \), and 5\(^{st}\) level of \( \text{WB}_1 \) and \( \text{WB}_2 \) are selected as the optimum values.

### TABLE IX. HERE

Fig. 17 shows the results of the detailed analysis of prototype SynRM. In the application of vehicles, when starting from zero to base speed and to overcome the initial inertial force, the scooter motor must be able to produce its maximum torque (at least two to three times) [12], [31]-[32]. Therefore, the motor needs a high starting current and torque. However, the amount of this current for the synchronous reluctance motor is less than the same current for the induction motor. The area shown in the efficiency map (Fig. 17) represents the area that satisfies the torque limit at the 1500 rpm speed.

### FIG. 17 HERE

### VIII. THERMAL ANALYSIS

Finally, to ensure a safe operation of the selected motors at powers below 300 W (Case 1) and also up to 1 hp (Case 6), thermal analysis is performed. Based on Fig. 18, the hot-spots of the two cases are around the slots of the stator which have the maximum values of 50 and 106 degrees of centigrade, respectively. These values are acceptable based upon the insulation class of the used materials.

### FIG. 18 HERE

### IX. PROTOTYPING AND EXPERIMENTAL SETUP

A six-pole SynRM prototype is manufactured in order to be tested and then, its output torque value gets compared with the FEM simulation results. In addition, an evaluation of the proposed strategy can be performed consequently. Different parts of this prototype are shown in Fig. 19. The stator is fixed to one side of the motor housing with three strong rods and the rotor is mounted on a central shaft which is on a bearing ready to be connected to the load. The final test is performed to confirm the analytical results and FEM.

### FIG. 19 HERE

### TABLE X. HERE

The prototype is tested in a laboratory equipped with the ABB ACS140 Multi-drive system. The resulted specifications of the prototyped SynRM are tabulated in Table X. Fig. 20 shows the comparison of the torque measured by FEA at different angles of the rotor at the nominal peak current of 10 Amps and the nominal speed of 1500 rpm. As shown in Fig. 20, the difference between experimental and simulation results can be attributed to the inaccuracy of calculations and practical measurements and also using
In this paper, different designs of synchronous reluctance motor (SynRM) are developed for electric scooter motors considering the geometrical dimensions imposed by the shape of the scooter ring. Consequently, the design requirements in terms of electromagnetic and mechanical issues of the motor with average high torque and low torque ripple are considered. Initially, based on the similarity between the flux line and shape of flux barriers, an analytical method is developed by using the concept of variable reluctance in SynRM. Accordingly, six motors with the same dimension and also with six different rotors are selected from all possible cases. Then, the optimal shape of the flux barriers in the rotor of each motor is determined through a multiple-step design which includes the Taguchi optimization method and sensitivity analysis. At all stages of the tests, changes in the effective parameters on the motor performance are conducted by FEM analysis, and the percentage of impact weight of each of these parameters on the output objective function is shown. In order to utilize the optimization method effectively, all selected synchronous reluctance motors are optimized and the results of average torque and torque ripple are compared with the initial designs. Finally, thermal analyzes are performed to confirm the proper operation of the motor at the rated currents of two specified SynRM. Experimental results of a prototype six-pole SynRM validate the accuracy of the proposed design method.

**X. Conclusion**

In this paper, different designs of synchronous reluctance motor (SynRM) are developed for electric scooter motors considering the geometrical dimensions imposed by the shape of the scooter ring. Consequently, the design requirements in terms of electromagnetic and mechanical issues of the motor with average high torque and low torque ripple are considered. Initially, based on the similarity between the flux line and shape of flux barriers, an analytical method is developed by using the concept of variable reluctance in SynRM. Accordingly, six motors with the same dimension and also with six different rotors are selected from all possible cases. Then, the optimal shape of the flux barriers in the rotor of each motor is determined through a multiple-step design which includes the Taguchi optimization method and sensitivity analysis. At all stages of the tests, changes in the effective parameters on the motor performance are conducted by FEM analysis, and the percentage of impact weight of each of these parameters on the output objective function is shown. In order to utilize the optimization method effectively, all selected synchronous reluctance motors are optimized and the results of average torque and torque ripple are compared with the initial designs. Finally, thermal analyzes are performed to confirm the proper operation of the motor at the rated currents of two specified SynRM. Experimental results of a prototype six-pole SynRM validate the accuracy of the proposed design method.

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Figure 1. Flow-chart of the proposed design method.
Figure 2: Required torque - speed characteristics for the electric scooter on different road slopes.

Figure 3: Force - speed characteristics of the electric scooter on different road slopes.

Figure 4: Exploded view of SynRM and Gearbox.

Table I: General specifications of the motors.

| Parameter | Definition               | Value       |
|-----------|--------------------------|-------------|
| $P_o$     | Range of Power           | 0.15-0.75 kW|
| $N_s$     | Rated speed              | 1500 (rpm) |
| $D_{os}$  | Stator Outside Diameter  | 150 (mm)   |
| $D_{or}$  | Rotor Outside Diameter   | 90 (mm)    |
| $P.F$     | Power factor             | 0.7        |
| $\eta$    | Motor efficiency         | 0.85       |
| $Ma$      | Stator and rotor material| M27-24     |
| $L$       | Stack length             | 42 (mm)    |
| $I_F$     | Phase Current            | 9.5 (A)    |
| $G$       | Gearbox ratio            | 9.45       |
| $k_s$     | Laminations stacking factor| 0.95     |

Table II: Study cases.
| Parameter | Number of Pole | Number of Barriers | Number of Slot Stator |
|-----------|----------------|-------------------|-----------------------|
| Case1     | 4              | 3                 | 24                    |
| Case2     | 4              | 4                 | 24                    |
| Case3     | 6              | 3                 | 36                    |
| Case4     | 6              | 4                 | 36                    |
| Case5     | 8              | 3                 | 48                    |
| Case6     | 8              | 4                 | 48                    |

Figure 5. Flux lines distribution in a solid rotor

Figure 6. Geometry definition of the flux lines in a four-pole motor.

Figure 7. Geometrical view of the proposed rotor with known design parameters.
Figure 8. Magneto-motive force distribution diagram of a half pole of the rotor [25].

Table III: EACH LEVELS OF DESIGN VARIABLES.

| Variables Level | Level1 | Level2 | Level3 |
|-----------------|--------|--------|--------|
| \( k_w \)       | 0.4    | 0.5    | 0.6    |
| \( \Delta \hat{Y}q_1 \) (mm) | 0      | 1.5    | 3      |
| \( \Delta \hat{Y}q_2 \) (mm) | -1     | 0      | 1      |
| \( \Delta \hat{Y}q_3 \) (mm) | -1     | 0      | 1      |
| \( \Delta \hat{W}B_1 \) (mm) | -1     | 0      | 2      |
| \( \Delta \hat{W}B_2 \) (mm) | -1     | 0      | 2      |
| \( \Delta \hat{W}B_3 \) (mm) | -1     | 0      | 2      |

Table IV: Experimental plan of \( l_2^7 (3^7) \)

| Variables Level | \( k_w \) | \( Yq_1 \) | \( Yq_2 \) | \( WB_1 \) | \( WB_2 \) | \( WB_3 \) |
|-----------------|----------|-----------|-----------|-----------|-----------|-----------|
| 1               | 1        | 1         | 1         | 1         | 1         | 1         |
| 2               | 1        | 1         | 1         | 1         | 1         | 1         |
| 3               | 1        | 1         | 1         | 1         | 3         | 3         |
| 25              | 3        | 3         | 2         | 1         | 1         | 3         |
| 26              | 3        | 3         | 2         | 1         | 2         | 1         |
| 27              | 3        | 3         | 2         | 1         | 3         | 2         |

Table V: Taguchi optimization results.

| Parameter | Case1 | Case2 | Case3 | Case4 | Case5 | Case6 |
|-----------|-------|-------|-------|-------|-------|-------|
| \( T_{avg} \) (N.m) | 1.04  | 0.88  | 0.59  | 1.04  | 0.48  | 0.58  |
| \( T_{Ripple} \) (%) | 36.96 | 27.84 | 22.17 | 34.18 | 28.80 | 16.31 |

Table VI: The results comparison for all the cases.

| Study Cases | Initial design | Taguchi design | Optimal design | Initial design | Taguchi design | Optimal design |
|-------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Case1       | 0.99           | 1.04           | 1.10           | 56.40          | 36.96          | 36.05          |
| Case2       | 0.88           | 0.88           | 0.88           | 39.46          | 27.84          | 26.33          |
| Case3       | 0.54           | 0.59           | 0.64           | 30.16          | 22.17          | 12.19          |
| Case4       | 0.66           | 1.04           | 0.73           | 21.06          | 34.18          | 25.36          |
| Case5       | 0.47           | 0.48           | 0.58           | 30.44          | 28.80          | 28.47          |
| Case6       | 0.58           | 0.58           | 0.66           | 17.2           | 16.31          | 14.31          |

Figure 9. Torque of all motors in the optimized cases.
Figure 10: Torque characteristics: (a) Average torque, (b) torque ripple of all cases in optimization.

Figure 11. Inductance and the inductance difference of the d and q axes.

Figure 12. The saliency ratio in all cases.
Figure 13. Torque – current characteristic for the all optimized cases.

Figure 14. Torque of optimized motors at input currents from 9 Amps to 25 Amps: (a) Case 2, and (b) Case 6.
Table VII: DIFFERENT LEVELS OF DESIGN VARIABLES.

| Variable          | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|-------------------|---------|---------|---------|---------|---------|
| $\Delta Y_{q1}$ (mm) | -0.75   | -0.5    | 0       | 1       | 2       |
| $\Delta Y_{q2}$ (mm) | -2      | -1      | 0       | 0.5     | 1       |
| $\Delta W_{B1}$ (mm) | -1      | -0.5    | 0       | 0.5     | 1       |
| $\Delta W_{B2}$ (mm) | -1      | -0.5    | 0       | 0.5     | 1       |
| $k_{eq}$          | 0.3     | 0.4     | 0.5     | 0.6     | 0.7     |

Table VIII. Assignment of control factors and levels.

| No. | $\Delta Y_{q1}$ | $\Delta Y_{q2}$ | $\Delta W_{B1}$ | $\Delta W_{B2}$ | $k_{eq}$ | $T_{avg}$ (N.m) | $T_{ripple}$ (%) |
|-----|-----------------|-----------------|-----------------|-----------------|---------|-----------------|-----------------|
| 1   | 1               | 1               | 1               | 1               | 1       | 0.68            | 14.7            |
| 2   | 1               | 2               | 2               | 2               | 2       | 0.99            | 10.8            |
| 3   | 1               | 3               | 3               | 3               | 3       | 1.02            | 27.9            |
| 4   | 1               | 4               | 4               | 4               | 4       | 1.09            | 41.3            |
| 5   | 1               | 5               | 5               | 5               | 5       | 1.15            | 48.4            |
| 21  | 5               | 1               | 5               | 4               | 3       | 1.19            | 19.9            |
| 22  | 5               | 2               | 1               | 5               | 4       | 1.12            | 20.6            |
| 23  | 5               | 3               | 2               | 1               | 5       | 1.04            | 48.4            |
| 24  | 5               | 4               | 3               | 2               | 1       | 0.92            | 68.6            |
| 25  | 5               | 5               | 4               | 3               | 1       | 1.11            | 72.6            |
Table IX: Impact weight of Design variables.

| Variable | Impact weight on average torque | Impact weight on average torque ripple |
|----------|---------------------------------|----------------------------------------|
| $\Delta Y_{q1}$ | 14.63% | 9.33% |
| $\Delta Y_{q2}$ | 7.62% | 82.47% |
| $\Delta WB_1$ | 22.36% | 2.15% |
| $\Delta WB_2$ | 11.98% | 5.6% |
| $kw_q$ | 43.41% | 0.46% |

Figure 17. Efficiency map for prototype motor.
Figure 18: Temperature distribution of (a): Case 1 SynRM, (b): Case 6 SynRM,
Figure 19. Different parts of SynRM: (a) exploded view of the rotor, (b) lamination of the rotor, (c) The main parts of Motor, and (d) Experimental test-setup.

Table X: Specifications of the prototype motor.

| Parameter | Definition                        | Value  |
|-----------|-----------------------------------|--------|
| $P_o$     | Output Power                      | 0.15 kW|
| $N_r$     | Rated speed                       | 1500 (rpm)|
| $P.F$     | Power factor                      | 0.6    |
| $\eta$    | Motor efficiency                  | 0.83   |
| $P_{loss}$| Total losses                      | 28W    |
| $P_{cu}$  | Stator copper losses              | 21W    |
| $p_c$     | Core loss                         | 5.3W   |
| $P_{f \& W}$ | Friction and wind age losses | 1.75W  |
| $I_p$     | Phase Current                     | 10 (A) |
| $Copper_w$| Copper weight                     | 0.8kg  |
| $Stator_w$| Stator core weight                | 1.9kg  |
| $Rotor_w$ | Rotor core weight                 | 1.2kg  |
| $kst$     | Laminations stacking factor       | 0.95   |

Figure 20: Torque of SynRM; (a) FEA result, (b) Experimental result.
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