

Modeling of 6 to 4 Switched Reluctance Motor using Coefficient Method and Analytical Method

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Abstract

Electric kick scooter field has become famous this lately, and become another solution for electric vehicle. Switched Reluctance Motor has been chosen as the propulsion system in this application due to the advantages of this motor. Meanwhile, the issue of lack experience in electrical motor design is one of the hollow subjects in machine design field. Through design aspects, the Switched Reluctance motor is developed using a simple technique which is coefficients method. This method is to provide the easiest ways for other non-academic designer for those who has lack experience in motor design. A set of a coefficient to determine motor dimension is being set. Then, this technique will be referred to the existing analytical method to provide a design guideline and to validate this coefficient as the quick references to design the SRM. The aim is not to make a comparison between the methods but intend to provide another easiest solution to design the SRM motor. The modelling has been test using RMxprt tools the expectation from this method is the outcomes will be compatible with existing design.

Keywords: Switched Reluctance Motor, coefficients method, analytical method, RMxprt, electric vehicle

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1. Introduction

One factor of environmental pollution comes from the emissions of noxious gasses from internal combustion engine (ICE) and the lack of fuel efficiency during the burning process. Small EV such as kick scooter or electric bicycles become more attractive due to the increasing of traffic congestion which contributes to the environmental pollution. A fully EV can constitute a zero emission vehicle. It use electric motor for propulsion and battery as storage device [1]. An efficient EV must be able to provide a large torque under the base speed and able to operate at constant power over wide speed range.

Typical characteristics of an electric motor in application highlights a few points in electric motor development such the rated power which is the capability of a motor to produce work during acceleration period, the rated torque, sizing, volume and the ability to drive passing time and distance to develop larger constant power in area ratio. Switched Reluctance Motor (SRM) offers several advantages to fulfill EV application development. To have an optimum design, it starts with the determination of motor dimensions or design geometry. This research is basically done to provide a preliminary guideline to design SRM for a small scale EV application.

Past studies have shown that motor dimension was determined using two common techniques, namely analytical and numerical technique. Derivation of machine dimension was determined according to the geometry and relates to the output equation of such output power. Analytical method needs time to compute full dimension of a machine while the research only need a few basic dimension structures to build a SRM. Meanwhile, FEA provides a fast computation on the results but finding an optimum design is difficult. Sometimes, researchers only need a few preliminary values of motor dimension to design a motor. Later, the model was strengthened with other fine-tuning tools such FEA to have an optimum design. Based on a few techniques reviewed [2], the dimensions of a machine were determined by insufficient design experience and lack of design technique. Motor designing has to start from the beginning of sizing and dimensions. Throughout that design, this research applies an approach with a simple technique instead of using the existing technique. The aim is to provide simple technique for

developing SRM for those who lack experience in motor design with the aid of analytical technique which already existed in the development of motor design.

1.1. SRM Design Parameter

In order to define a suitable design on SRM for kick scooter application, a design requirement was set up in the beginning of the modeling. The parameters such as high efficiency, high torque, power density, and reasonable speed range were considered at the earlier design stage. This motor was built based on the conventional 6/4 design of SRM but used the proposed technique as a preliminary guideline to have an exact structure of motor. This input parameter of SRM was following the design limitation of [3] as a benchmark for this motor. This design had a fixed outer diameter which is 100 mm due to limitation of space to install the machine and this dimension is suitable for a small scale application. SRM rated speed was set to 500 RPM according to the limitation of speed for kick scooter. Usually, normal rate for kick scooter is 25 m/h for 20-meter distance. Insufficient energy to provide enough power to run this motor is another limitation in design, thus this motor was set to 24V, relatively to typically rated voltage which is 24 V to 42V. Maximum current was set up to 10A considering the worsening case to the motor, while the rated current is at 6A. The design procedure of SRM for this kick scooter starts with design restriction as listed in Table 1.

Table 1. Design restriction of SRMs

Mechanical Output Power	350 W
Rated Speed	500RPM
Rated torque	6.68N.m
Voltage input	24V
Peak phase current	10A
Axial Length	30.1mm

1.2. Coefficient Methods

The process of designing an SRM has to be enclosed with a proper design procedure in order to ensure an efficient performance of the motor. In this study, SRM structure was built based on conventional SRM geometry as in Figure 1, but dimensions of the motor were defined using a coefficient method. This dimension of the motor structure was determined using the proposed method, which was coefficient method. Here, coefficient method was defined by gathering SRM motor dimensions from numerous technical publications [4] [3] [5] [6] [7] [8] to define the optimum or feasible design ratio from various geometry dimensions. The process to define the coefficient was taken from every motor dimensions of previous literature. A few samples of SRM dimensions were collected and summarized into a set of coefficient. Consequently, the design boundary was defined by measuring the ratio of every dimension in SRM structure. As an example, if the outer diameter of the stator is 96.56 mm and the inner diameter is 48.86, the ratio will be around 0.51 mm. A complete dimension of SRM can also be determined by using the same method. From the ratios, a set of coefficients were summarized in Table 2.

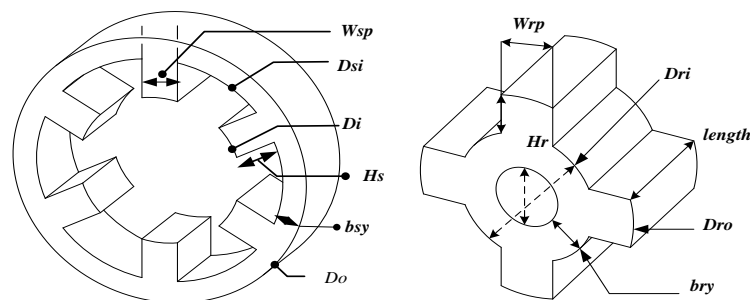


Figure 1. SRM basic geometry stator and rotor

Table 2. Design SRM using coefficient method

Parameter	Symbol	Coefficient	Remarks
Inner stator to Outer diameter of stator	Dsi : Do	0.258-0.88	K1
Inner diameter of stator to bore stator	Dsi: Di	0.13-0.54	K2
Bore rotor to Outer diameter of stator	Dro:Do	0.56-0.87	K3
Inner rotor to bore diameter rotor	Dri: Dro	0.51-0.87	K4
Rotor bore diameter to shaft diameter	Dro: Dsh	0.32-0.57	K5
Stack length to rotor bore	Length:Dro	0.32-3.8	K6
Stator yoke thickness to rotor yoke thickness	bsy :bry	0.98-1.0	

1.3. Analytical Method

To validate the coefficient method as a quick references design guide, an analytical method was performed to compare between two models, to see whether the coefficient method can give the same characteristic of this machine or not. Method from [9] was used to find the performance characteristics of the switched reluctance motor. In this case, the outer diameter of this machine has been fixed. Thus, another initial assumption was made to define the bore diameter. By using Krishnan method, the SRM procedure was developed by analytical method which derives from the output machine characteristics. Based on Krishnan method too, the bore diameter of stator was determined by using the output power equations. From that, another motor dimensions and excitation conditions will be obtained. The full dimension was used for analysis in finite element software. Table 3. describes the input parameters used in the analytical method.

Table 3. Input parameters using analytical method

Parameter	Remarks
Input power	350W
Voltage input, Vm	24V
Coefficient efficiency, ke	1
k1	$\pi^2 / 120$
k2	0.65 < k2 < 0.75
Electrical Loading, Asp	25000 < Asp < 90000
Ratio length to bore , k (Non-servo application)	0.25 < k < 0.70
Maximum Flux density (Aligned Position)	1.5T

2. Modeling Method

This section will define how the modeling on these two method were conducted. The preliminary structure of SRM will be build using the two method which are coefficient method and the analytical method. Output of these two method will be used to know the basic design characteristic of SRM.

2.1. Modeling using Coefficient Method

The preliminary SRM structure was determined using a simple mathematical equation to define all geometry dimensions as shown in Table 4. The complete SRM dimension was checked with the rules of thumb to ensure it is compatible and able to achieve an optimum design. At the initial stage, the outer diameter was set to be fixed at 100 mm. The average coefficient value was chosen to be used along with the simple equations and the pre-dimension are listed in Table 4. Later, the fine tune process was executed to achieve the targeted torque without the effect of saturation as tabulated in Table 5.

Table 4. Dimensions solutions using coefficient method

Parameter	Equations
Bore Diameter of Stator	$Dsb = k1 \times Do$
Inner diameter of stator	$Dsi = Do - (Dsb \times k2)$
Bore of rotor	$Dro = Do \times k3$
Bore inner rotor	$Dri = Dro \times k4$
Shaft diameter	$Dsh = Dro \times k5$
Width of stator pole	$Wsp = \left(\frac{Dri}{2}\right)\beta_s$
Width of rotor pole	$Wrp = \left(\frac{Dri}{2}\right)\beta_r$
Stator Yoke thickness	$bsy = \left(\frac{Do - Dsi}{2}\right)$
Rotor Yoke thickness	$bry = \left(\frac{Dri - Dsh}{2}\right)$
Stack Length	$Length = \left(\frac{Dsb}{k6}\right)$

Table 5. Overall preliminary design dimension using coefficient method

Description	Symbol	Initial Dimension (mm)	Fine Tuning1 (mm)	Fine Tuning 2 (mm)	Fine Tuning 3 (mm)
Stator outer diameter	Do	100	100	100	100
Stator bore diameter	Di	56.7	57	57	57
Stator inner diameter	Dsi	81	84	84	84
Stator pole height	Hs	12	14.7	14.7	12
Stack length	l	39	39	30.1	30.1
Stator yoke thickness	bsy	9.5	9	8	8
Rotor outer diameter	Dro	56	56.7	56.7	56.7
Rotor bore diameter	Dri	39.3	39.7	39.7	40.7
Rotor pole height	Hr	8.35	8.3	8.3	8.3
Rotor yoke thickness	bry	11	8.5	8.5	8
Shaft Diameter	Dsh	18	20	20	20
Air Gap	Ag		0.3 mm		

2.2. Design Solutions using Analytical Method

This method was derived from the output equations developed in a manner similar to a conventional rotating machine. The bore diameter was set within the range of 0.54 to 0.63 according to [10] due to design limitations. The bore diameter was then decided to be between the range and the fixed outer diameter was set to 100 mm. Next, a lamination structure was determined using the previous outer diameter (Equation 2.1 – 2.5). The axial length can be determined using Equation 2.1.

$$Length = k \times Dro \quad (2.1)$$

Prior to defining another dimension, the air gap cross-sectional, area stator pole, stator pole flux, and magnetic field intensity were determined to calculate next lamination structure. Calculations for air gap cross-sectional, area of stator pole, stator pole flux, and magnetic field intensity were made using the following equations, respectively.

$$Ag = \left(\frac{Dro}{2} - 1g\right) \left(\frac{\beta_r + \beta_s}{2}\right) - length \quad (2.2)$$

$$Asp = \left(\frac{Dro \cdot L \cdot \beta_s}{2}\right) \quad (2.3)$$

$$\phi = B \cdot Asp \quad (2.4)$$

$$Hg = \left(\frac{B \cdot Asp}{2\mu_o \cdot Ag} \right) \quad (2.5)$$

The relationship between numbers of turn per phase is related to the allowable current flow through the motor with the area of stator pole as in Equation 2.6. Basically, the peak phase current was initially assumed to perform this equation. Then, the area of the conductor in Equation 2.7 was determined according to the maximum allowable current density in the winding. The height of stator was determined using Equation 2.8.

$$Tph = \left(\frac{Hg \cdot 2lg}{Ip} \right) \quad (2.6)$$

$$ac = \frac{Ip}{J\sqrt{q}} \quad (2.7)$$

$$hs = \left(\frac{Do}{2} \right) - \left(\frac{Dro}{2} \right) - bsy \quad (2.8)$$

The width of stator pole need to be considered in order to define the stator yoke thickness so it will be appropriate with the mechanical robustness and minimization of vibration aspects. This is because the stator yoke thickness should be within the width of stator pole value and 50% of the width of stator pole ($Wsp > bsy > 0.5Wsp$).

$$Wsp = Dro \sin \frac{\beta s}{2} \quad (2.9)$$

The consideration of large air gap is a must to provide a high ratio between aligned and unaligned inductance while the motor rotates. Rotor yoke thickness value must be between the value of width stator pole, within 50% width of stator pole, and 75% width of stator poles ($0.5Wsp < bry < 0.75Wsp$). The height of rotor pole can be determined using the Equation 2.10. The overall dimensions of SRM were determined using analytical method and are shown in Table 6. The design were insert into Finite element software ANSYS MAXWELL 2D to predict the initial output performance in terms of the winding profile, torque production, and inductance profile. Furthermore, fine tuning has been made to achieve the design needed.

$$hr = \frac{Dro}{2} - lg - bry \quad (2.10)$$

Table 6. Dimension of SRM using Analytical Method

Description	Symbol	Initial dimension (mm)	Fine Tuning 1 (mm)	Fine Tuning2 (mm)	Fine Tuning3 (mm)
Stator outer diameter	<i>Do</i>	100	100	100	100
Stator bore diameter	<i>Di</i>	57	57	58	59
Stator inner diameter	<i>Dsi</i>	82	84	84	84
Stator pole height	<i>Hs</i>	13.15	13.73	13.73	13.73
Stack length	<i>l</i>	32	30.1	30.1	30.1
Stator yoke thickness	<i>bsy</i>	8.5	8	8.5	8
Rotor outer diameter	<i>Dro</i>	56.7	56.7	57.5	58.5
Rotor bore diameter	<i>Dri</i>	23.325	23.65	24.05	24.55
Rotor pole height	<i>Hr</i>	9.08	9.05	9.05	9.95
Rotor yoke thickness	<i>bry</i>	9.9	9.5	9	9.5
Shaft Diameter	<i>Dsh</i>	20	20	20	20
Air Gap	<i>Ag</i>		0.3mm		

2.3 Simulation Setup

In Finite Element Analysis (FEA), RMxpert is a rotating machine expert and it is a program package produced by Ansoft. RMxpert was used to pre-assume the output performance of the motor. This tool was built from a combination of analytical and magnetic circuit equation that was used to predict the performance of design motor before being analyzed using 2D FEA. RMxpert plotted a few characteristics of the motor design. Here, the modeling of SRM was integrated with the synchronized commutation of phase current with precise rotor position. The switching sequence of this motor was energized on each step pulse (turn on an angle) and was switched off at the turn off angle. Lead angle trigger was set to zero and the trigger pulse width was 120 degree per phase. The air gap between Stator laminations and Rotor laminations was set to 0.3 mm due to having a low resistance in the magnetic circuit of the motor and due to practical manufacturing tolerance.

3. Modeling Result

This section will present the result on modeling SRM using two methods which are coefficient and analytical method. The result shows the effect on the predicted output torque profile, efficiency, and output power and flux linkages.

3.1. Coefficient Verification using RMXPERT

A few tests of fine tune were done to predict the preliminary output performance of SRM design as shown in Figure 2. The initial dimension based on the coefficient method is 2.42 N.m starting torque with 1.48 N.m rated torque. While fine tune combination 1 gives output torque of 2.3 N.m starting torque and 1.36 N.m rated torque. Then, through the fine tune test, fine tune combination 2 produced 8.374 N.m starting torque. From the curve, as the rotor rotates at 500 RPM, the estimated output torque is 3.8 N.m compared to the initial value. Next, the fine tune 3 gives 8.3 N.m starting torque and 2.9 N.m rated torque. The initial dimension for predicted efficiency gives 15.22% efficiency, while fine tune 1 produced 13.83%. Through fine tune test 2 plus fine tune 3, the efficiency is 40.6% and 40.5%. Figure 2(c) shows that the output power for initial dimension is 77.73 W, while fine tune combination 1 dimension gives output power of 71.14W. Fine tune combination 2 output power is 167.7 W and last fine tune combination 3 gives output power 168 W. According to Figure 2(d), the Predicted flux linkage for initial dimension is 0.06 Wb, for combination fine tune test 1 is 0.053Wb, while fine tune test combination 2 is 0.118 Wb, and the fine tune test 3 is 0.101 Wb.

3.2. Analytical Verification using RMXPERT

The initial value based on analytical method in Figure 3 (a) the output torque is 6.87 N.m starting torque with 2.59 N.m rated torque. While fine tune combination 1 gives output torque 8.07N.m starting torque and 3.17 N.m rated torque. Then, through fine tune test, fine tune combination 2 produce 8.329 N.m starting torque and as the rotor rotates at 500 RPM, the estimated output torque is 3.38 N.m compared to the initial value. Next, fine tune 3 gives 7.35 N.m starting torque and 2.92 N.m rated torque. The initial dimension for predicted efficiency gives 39.28% percentage of efficiency, while fine tune 1 produced 40.73%. From the fine tune test 2 plus fine tune 3, the efficiency is 40.38% and 39.8%, respectively. Figure 3(c) shows that the output power for initial dimension is 135.11W, while fine tune combination 1 dimension gives output power 165.21W. Fine tune combination 2 output power is 176.35 W, and lastly, fine tune combination 3 gives output power 131.9 W. Based on Figure 3(d), the predicted flux linkage for initial dimension is 0.116 Wb, for combination fine tune test 1 is 0.1192 Wb, while fine tune test combination 2 is 0.1195 Wb and the fine tune test 3 is 0.1167 Wb.

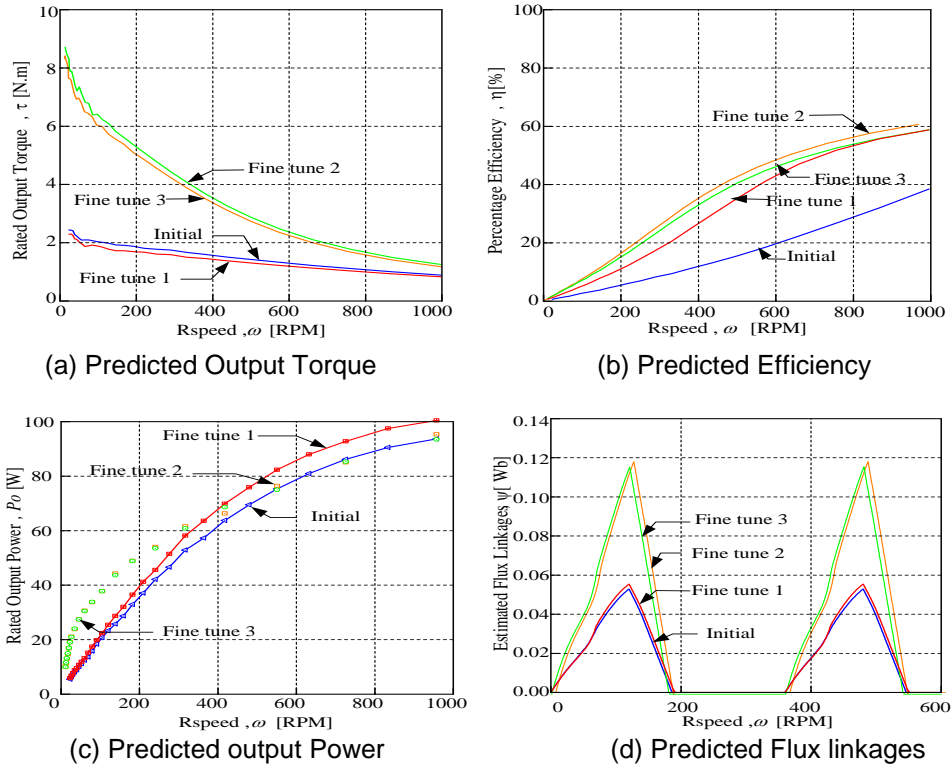


Figure 2. Preliminary Output Performance at different fine tune

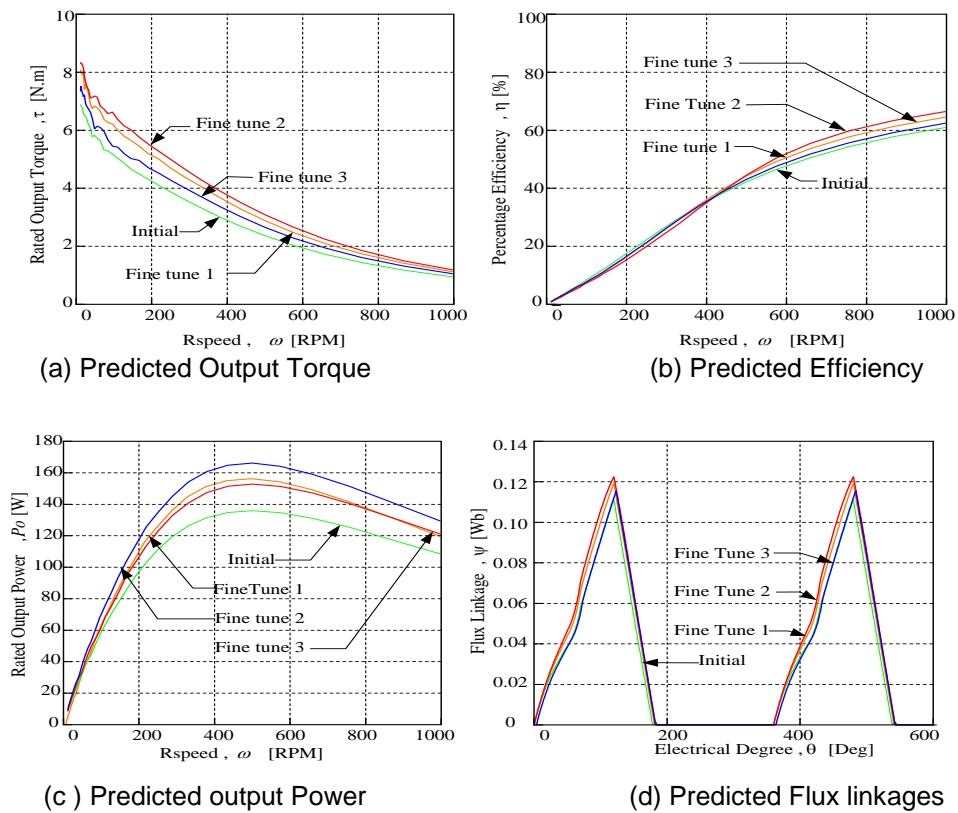


Figure 3. Output Performance at different fine tune by Analytical Method

4. Conclusion

These two methods above had been executed to predict the output performance of the two modeling using two different methods. The coefficient method was initially done to have more preliminary dimensions without concerning the saturation effects. Hence, through this method, a designer will have a preliminary design to model the SRM motor and strengthened it with other tools design. Meanwhile, an assumption in analytical method is required prior to using the equation. This is caused by the limitations on the fixed outer diameter value since the existing analytical assumption was used to start with the derivation on the output power of the motor.

Results showed that the coefficient method can be considered as a preliminary method to define SRM geometries. Then, it can be an aid with the analytical method to have more validation on the coefficient method. In fact, both methods needs initial assumptions because the outer diameter has been set up to be fixed to a certain value. From the final dimension model, the predicted analytical model output torque is 3.38 N.m and the model of coefficient method is 3.2 N.m. The efficiency of the coefficient method is 40.6% compared to 40.4% analytical method. Output power of analytical method is 167.7 W while coefficient method output power is 165.2 W. Through this, it can be concluded that, coefficient method can be used as the guideline and compatible with the existing method.

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