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Design investigation for continual torque operative performance of PMSM for vehicle

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Abstract. The increasing trend of population and its one of the requirements, on road vehicles are increasing. In addition, rural to urban development and subsequent deforestation leads to ozone depletion, climate change, loss of biodiversity and finally global warming encourages to research to give the substitute for IC Engine vehicles by developing electric vehicles. Present 20–35% of world economy is driven by IC Engine vehicles and now upcoming challenge is to develop equivalent and better technical solutions to sustenance environment with green vehicles. The existing developed electric vehicles has limitation to work under controlled environment and suitable for good road conditions. However, the requirement is to develop the continual torque operative motor which can be suitable for Indian road, Indian weather conditions and which can overcome the IC Engines. This is preliminary design investigation of motor for operative torque performance considering the different design parameters for stator slot configurations, slots/pole ratios, rotor configurations, combination of different types of magnetic materials, stack length, back iron, and dimensions of the effective magnet. The design simulation is done in RMxprt as per the important required characteristics of the electric vehicles (EVs).

Keywords. PMSM; RMxprt; EV; IPM; IC; IM; PMBLDC; SRM; BLDC; AC; LSPMSM.

1. Introduction

As per the market demand/requirement of EVs, an electric drive has been developed and hence the electrical machines such as DC, Induction and Permanent Magnet Machines are reviewed and evaluated [1]. The features of IM, PMBLDC and SRM have been compared and studied with the result that the SRM is the most suitable motor for EVs [2]. PMSM can be the choice according to the efficiency and reliability. The challenges in PMSM are high cost and flux weakening on limiting the electric loading [3]. The IPM machines have better performance, simple construction and short end connections [4]. The advantages of BLDC, AC machines and SRM suitable for Electric and Hybrid Electric Vehicles as per the requirements of torque, power density, speed ranges and efficiency have been studied [5]. The efficiency of the LSPMM can be improved by changing the rotor structure. It also results in high air gap flux [6]. The stator bore diameter, stack length and efficiency is changed by changing the material of the magnet [7]. The industrial high performance drive systems are already using PMSMs which are the imported one. The development of the PMSM is necessary to avoid importation. So, the stator and rotor structure would be the main design consideration for the better performance [8]. The slotted and slot less stator, shape of the magnet and rotor geometry, saliency and field weakening take part in improving the motor performance and structure [9, 10].

The objective of this paper is how to strengthen the design of the PMSM and analyze the performance if any minor variation in design parameter and manufacturing inaccuracy, results obtained by RMxprt. The outcomes are then validated with the upcoming proto-model of the machine and the key requirements of the EVs.

The basic requirements of this study are to understand the basic concept of PMSM design theory and to focus on key parameter for its performance improvement to maintain continual torque in vehicle application.

Here, the PMSM rating of the machine is tentatively considered by theoretical and experimental basis and this is as the bare minimum requirement of the two person load carrying capacity vehicle. As per the motor design parameter, the stationary part (stator), stator slot, and rotating part (rotor), winding layout, pole structure, magnet materials and critical dimensions have been calculated. By changing the key parameters, the performance of the motor is monitored in simulation and based on high performance result design parameters are optimized.

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2. Benefits and limitations of EVS

The benefits of EV are:

1. Air pollution free environment
2. Noise Pollution free (Silent Operation)
3. More Efficient than Internal Combustion (IC) Engine as Mechanical Losses are drastically reduced
4. Re-generate the energy during braking, Gravity slope
5. Simple in control
6. Less wear and tear maintenance
7. Reduce Fuel import burden, indirect support to country economy
8. Anywhere and simple way for charging,
9. Manufacturing process steps are less

The limitations of the EV are:

1. Requirement of Smart and eco-friendly Energy Storage System which can Efficiently operate in ambient temperature
2. Handling and Disposal of Energy Storage material
3. Self-discharge and limited life span of Energy storage
4. Energy storage charging time
5. Availability of Magnetic raw material

The main factors causing the limited use of the EVs from the customer point of view are: (1) Price – the cost of the battery made the EVs expensive. (2) Size – to reduce the energy consumption, the size of the vehicle is small. (3) Charging Time – the time for charging the vehicle is long.

2.1 *Electric machines used in EVs*

The electric machines used in vehicle works as electro-mechanical rotary device, its purpose is to convert energy (electrical to mechanical energy conversion) and are designed to deliver the power (torque) to the driving axle wheels.

2.2 *PMSM basic*

The interior PMSM has its magnets dormant inside the rotor. The *q*-axis inductance *Lq* in the interior PMSM can be much larger than the *d*-axis inductance *Ld*. The larger difference in the *d* and *q*-axes inductances makes the interior PM more suitable for flux weakening operation, delivering a wider constant power region compared to the surface-mount or inset PMSMs. The extended constant power range capability is extremely important for an electric vehicle. Because of the unequal reluctance paths in the direct and quadrature axes, a reluctance torque exists in dormant and inset PMSMs.

3. Design considerations

Prior to start design of machine, it is necessary to understand related application, specific requirement and key design parameters which can leverage the performance of machine. Below equation is common to all topologies.

The mathematical equations which would lead to the final design parameters are of the torque and motor size which are the basic concepts.

$$F = N B_g L I_s \tag{1}$$

F – Force experienced by the rotor
N – Number of magnet poles
B_g – Air gap flux density
L – Core length
I_s – Slot current

The relation of the force with all the above-mentioned terms is given by the above equation.

1. N – Number of magnetic poles: It is directly proportional to force produced, an increase in number of magnetic poles resultant force is increased,
2. Air gap flux density (B_g): It is also directly proportional to force produced, increase in flux density increases the force.
3. Core length (L): Core length is directly proportional to the force produced; increase in length increases the force.

Even though all the above three parameters are directly proportional to force produced, here is some theory to select appropriate value, as all these are co-relating some adverse impact with each other. For more details if we look for selection of number of poles (N) – as increase in number of pole results in reduction in magnet width and increment in leakage flux and hence reduction in air gap flux density. The number of poles is selected according to optimum air gap flux density and the motor performance.

Same way for calculation of Air Gap Flux Density (B_g) need to focus on permeance coefficient (PC) of the magnetic circuit and increase in PC increases the magnet length which will decrease the effective air gap length. Hence, the air gap flux density must be within the saturation limit and to avoid the increase in cogging force

Finalization of core length (L) – this is critical parameter as this is directly related to power density and motor efficiency. The increase in core length results in increase in force, mass, volume of the motor, resistive losses with poor power density and efficiency. Hence, a required force can be achieved by having small core length.

Stator slot Design: The torque is developed by the interaction between the flux density and current. It is possible with the stator structure with slots, phases, poles and windings. The number of slot per pole per phase N_{SPP} is calculated by taking the ratio of number of slots per phase N_{SP} and the number of poles N_m as follows.

$$N_{SPP} = \frac{N_{SP}}{N_m} \tag{4}$$

This ratio need not be one but can be greater than one. When chosen as greater than 1, the back emf distribution tends to become more sinusoidal or smoother and harmonic content of the back emf decreases. In addition, the cogging torque is reduced in addition to back emf smoothing.

Cogging torque is the unwanted element in PM motor design. The cogging torque need to reduce and it plays an important role in motor design. Cogging torque is produced due to the interaction between the rotor poles and the stator saliency. The cogging torque can be given as follows.

$$T_{cog} = -\frac{1}{2}\phi_g^2\frac{dR}{d\theta} \tag{5}$$

In this equation, ϕ_g is the air gap flux and R is the air gap reluctance.

The rotor has an even number of magnets and the number of pole pairs on the rotor can be estimated as

$$\text{The no. of rotor pole pairs} = \frac{\text{No. of magnet poles facing the air gap } (N_m)}{2}$$

3.1 *Design approach for the Radial Flux Motor Design*

In design of PM motor design various parameters are involved such as geometrical, magnetic and electrical. While designing some of the parameters are necessary to fix and it is up to the designer.

1) **Geometric Parameters:** The various radii are

R_{sb} – *Stator Back Iron radius*
R_{so} – *Stator outside radius*
R_{si} – *Stator inside radius*
R_{ro} – *Rotor outside radius*
R_{ri} – *Rotor inside radius*

These are associated with the back iron width w_{bi}, slot depth d_s, air gap length g and magnet length l_m.

The pole pitch at the inside surface of the stator is related to the angular pole pitch by

$$\tau_p = R_{si}\,\theta_p$$

Where

$$\theta_p = \frac{2\pi}{N_m}$$

is the angular pole pitch in mechanical radians and the coil pitch at the rotor inside radius is

$$\tau_c = \alpha_{cp}\,\tau_p$$

Where

$$\alpha_{cp} = \frac{\tau_c}{\tau_p}$$

is the coil pole fraction. The slot pitch at the rotor inside radius is

$$\tau_s = R_{si}\,\theta_s$$

Where

$$\theta_s = \frac{2\pi}{N_s}$$

is the angular slot pitch in mechanical radians. The tooth width is given by

$$w_t = \tau_s - w_s$$

The slot depth is given by

$$d_s = R_{sb} - R_{ro} - g$$

Which must be greater than zero.

2) **Magnetic parameters:**

The flux from each magnet splits equally in both the stator and rotor back irons and is coupled to the adjacent magnets. Therefore the flux in back iron is

$$\phi_{bi} = \frac{\phi_g}{2}$$

Then the width of the back iron is estimated as follows by using flux density in back iron.

$$w_{bi} = \frac{\phi_g}{2\,B_{max}\,k_{st}\,L}$$

Where, k_{st} is the lamination stacking factor.

There are some slots, teeth per magnet pole and hence the air gap flux travels through teeth of number of magnet poles (N_{sm}) from each magnet. The tooth width is determined as follows.

$$w_{tb} = \frac{\phi_g}{N_{sm}\,B_{max}\,k_{st}\,L} = \frac{2}{N_{sm}}\,w_{bi}$$

3) **Electrical parameters:**

The electrical parameters of the motor include resistance, inductance, back emf and current.

Torque: To estimate the electrical parameters, it is important to specify the relationship between the torque and other motor parameters.

$$T = \left(N_m\, B_g\, L\, n_s\, i\right) R_{ro} \tag{6}$$

The force is the product in parentheses, refer Eqs. (1). The interaction between the magnet poles (N_m), air gap flux density (B_g), conductors in number of turns per slot n_s carrying a current i and exposing the air gap flux density B_g over a length (L) produces force.

Now, the number of turns per pole per phase is needed to get the final torque equation with distribution, pitch and skew factor as follows.

$$\begin{aligned} n_{tpp} &= N_{spp}\, n_s. \\ T &= N_m\, k_d\, k_p\, k_s\, B_g\, L\, N_{spp}\, n_s\, i R_{ro} \end{aligned} \tag{7}$$

Back emf: The back emf at rated speed w_m can be estimated by using Eq. (7) and the input–output power relationship.

$$\begin{aligned} e_{max} &= \frac{T\, w_m}{i} \\ &= N_m\, k_d\, k_p\, k_s\, B_g\, L\, N_{spp}\, n_s\, R_{ro}\, w_m \end{aligned}$$

Current: The required current for the desired torque is the slot current. Its peal or rms value can be determined. The peak slot current is the value representing the worst case condition. The total slot current is the current carried by the number of turns per slot.

$$I_s = n_s\, i$$

Refer Eq. (7) and the slot current is

$$I_s - \frac{T}{N_m\, k_d\, k_p\, k_s\, B_g\, L\, N_{spp}\, R_{ro}}$$

Now, the phase current is

$$I_{ph} = \frac{I_s}{N_{ph}\, n_s} \tag{8}$$

The slot current flows through the conductors occupying the slot cross-sectional area. The part of the slot area is occupied by the conductor insulation, insulation between the conductors and additional insulation placed around the slot periphery. Finally, some fraction of the total cross-sectional is occupied by the slot conductors. This fraction is the conductor packing factor.

$$k_{cp} = \frac{Area\ occupied\ by\ conductor}{total\ area} \tag{9}$$

Resistance: The phase resistance is the function of the winding layout and the number of slots per pole per phase. It determines the copper losses of the motor. The slot and the end turn resistances with slot cross-sectional area A_s can be represented by the following equations.

$$R_s = \frac{\rho\, n_s^2\, L}{k_{cp}\, A_s}$$

$$R_e = \frac{\rho\, n_s^2\, \pi\, \tau_c}{2\, k_{cp}\, A_s}$$

The phase resistance with the given slots per phase and turns per slot would be as follows.

$$R_{ph} = N_{sp}(R_s + R_e)$$

Inductance: The phase inductance of the motor windings is the function of the winding layout and number of slots per pole per phase. It determines the maximum rate of change in phase current. It has three components due to the air gap, slots and end turns. The total phase inductance is

$$L_{ph} = N_{sp}\left(L_g + L_s + L_e\right)$$

Performance: Efficiency is the fundamental parameter which measures the performance of the motor. For the computation of efficiency, the losses are needed to be computed. The equation for efficiency with ohmic loss (P_r), core loss (P_{cl}) and stray loss P_s is as follows:

$$\eta = \frac{T\, w_m}{T\, w_m + P_r + P_{cl} + P_s}$$

The equations presented represent one of the many approaches for designing the rotating electrical machines. The other approaches are the different solutions, set of assumptions and are generally the same in all cases.

4. Design specifications

4.1 *Adjust speed permanent magnet synchronous machine*

The Adjust Speed PMSM improves the efficiency of the system due to the smaller size. PMSM makes the maintenance and installation much easier. In addition, it is able to sustain the torque at small revolutions per minute. The specification of the selected machine is

Operation Type: Motor
Mechanical Load Type: Constant Power
Power Output (kW): 3
Supply Voltage (V): 48
Number of Poles: 6
Speed (RPM): 3000
Frequency (Hz): 150
Loss due to Friction (W): 25
Rotor location: Inner
in service Temperature (°C): 75

The above specification of the motor then helps to decide the stator and rotor main dimensions.

4.2 *Stator construction*

Design calculations are carried out with given rating of the motor and some assumptions.

Stator Slots Number: 36
Stator OD (mm): 126
Stator ID (mm): 80
Stator Core Length (mm): 100
Stator CoreStacking Factor: 0.95
Steel Type: M19_24G
Designed Wedge Thickness (mm): 1.35861
Parallel Branches: 1
Conductors per Slot: 6
Skew Width (Number of Slots): 1
With these stator data, the following results have been obtained:

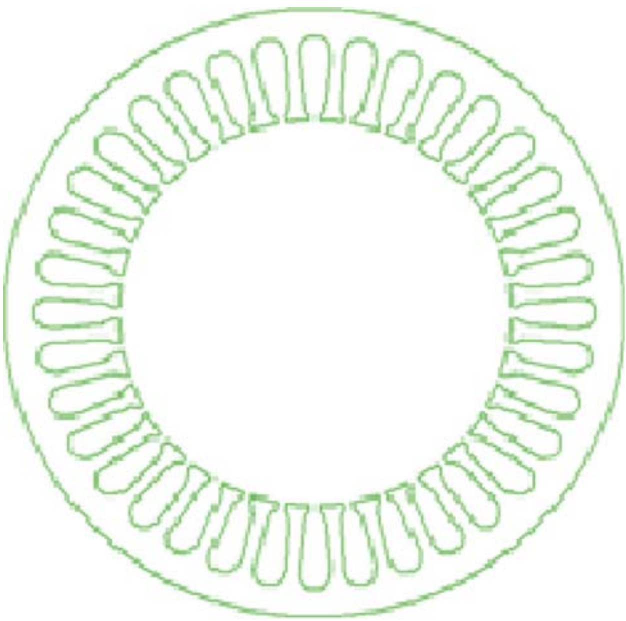

Figure 1. Stator with semi-enclosed slot.

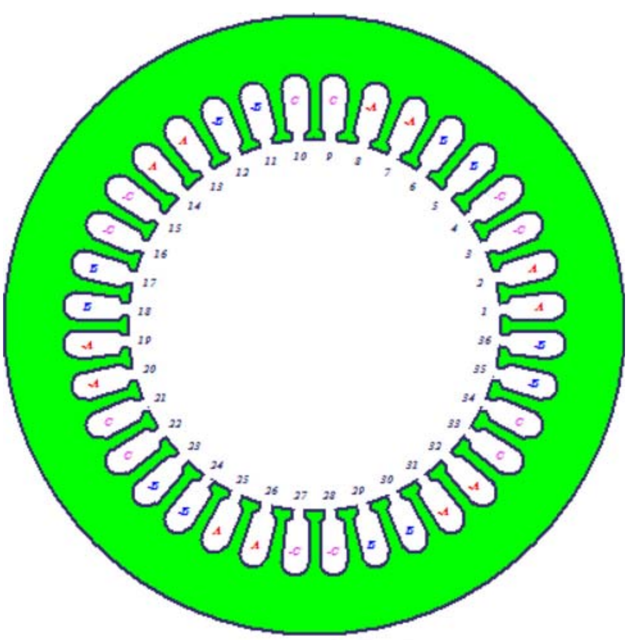

Figure 2. Stator winding layout.

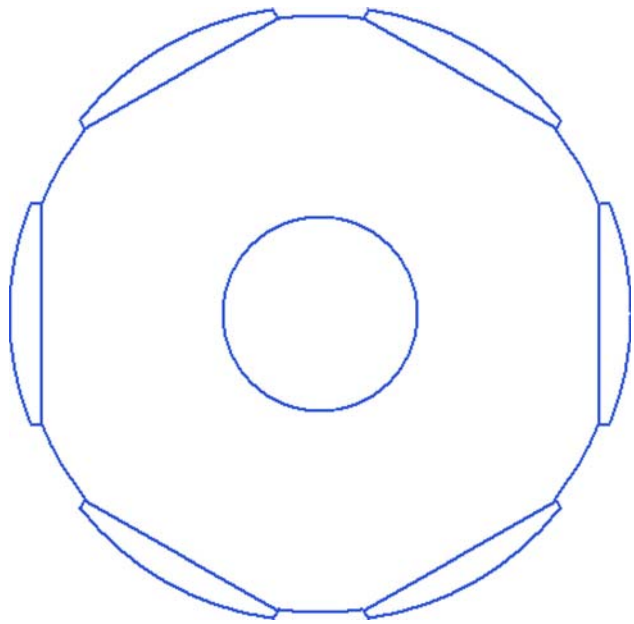

Figure 3. Surface Mounted Magnet Rotor

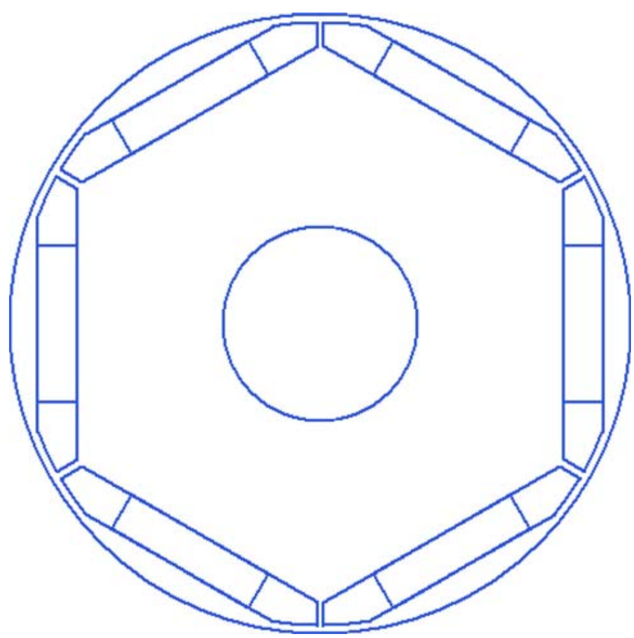

Figure 4. Bridge Type Magnet Rotor

Table 1. Effect of Stack Length of PMSM.

Stack length	Efficiency (%)	No-load current (amp)	Torque angle (degree)
70 mm	95.55	17.7	36.88
80 mm	95.12	60.43	35.73
90 mm	96.01	32.12	31.3
100 mm	*96.1*	*9.29*	*28.08*
110 mm	92.39	127.44	32.81
120 mm	94.05	92.34	28.53

Table 2. Effect of back iron of PMSM.

Back Iron	Efficiency (%)	No-load current (amp)	Torque angle (degree)
28 mm	96.16	13.57	28.67
31 mm	*96.1*	*9.29*	*28.08*
33 mm	96.07	12.146	28.19
35 mm	96	14	28.08

Table 3. Effect of Top Tooth Width of PMSM.

Top tooth width	Efficiency (%)	No-load current (amp)	Torque angle (degree)
3.46 mm	*96.1*	*9.29*	*28.08*
3.01 mm	96.16	13.57	28.67
2.56 mm	96.16	15.36	28.49
2.11 mm	96.02	22.55	29.15

Table 4. Effect of Rotor Structure of PMSM.

Rotor structure	Efficiency (%)	No-load current (amp)	Torque angle (degree)
Surface mounted magnet 3	88.91	131.8	8.56
Bridge type magnet	*96.103*	*9.29*	*28.08*
Surface mounted magnet 1	90.4	103.3	2.8
Surface mounted magnet 2	91.25	90.58	2.91
Interior circumferential	94.1	44.1	25.9

Top Tooth Width (mm): 3.46173
Bottom Tooth Width (mm): 3.10787
Average Coil Pitch: 6
Number of Wires per Conductor: 8
Wire Diameter (mm): 0.965
Slot Area (mm^2): 69.058
Net Slot Area (mm^2): 62.6222
Stator Slot Fill Factor (%): 71.3785
Coil Half-Turn Length (mm): 161.329
Wire Resistivity (ohm.mm^2/m): 0.0217 (figure 1).

4.3 *Winding arrangement*

The 3-phase, 2-layer winding can be arranged in 6 slots as below:

Angle per slot (elec. degrees): 30
Phase-A axis (elec. degrees): 105
First slot center (elec. degrees): 0 (figure 2).

4.4 *Rotor construction*

Once the stator dimensions are with us then it is possible to decide the rotor dimensions as follows:

Air Gap (mm): 0.5
ID (mm): 25
Length (mm): 100
Iron Core Stacking Factor: 0.95
Steel Type: M19_24G
Bridge (mm): 1

Rib (mm): 1
Pole Embrace (Mechanical): 0.7
Pole Embrace (Electrical): 0.666755
Max. Magnet Thickness (mm): 5
Magnet Width (mm): 20
Magnet Type: NdFe35 (figures 3, 4)

4.5 *Material consumption*

With the motor stator and rotor data, the material consumption is calculated and the results are as follows:

Armature Wire Density (kg/m^3): 8900
Permanent Magnet Density (kg/m^3): 7400
Armature Core Steel Density (kg/m^3): 7650
Rotor Core Steel Density (kg/m^3): 7650
Copper Weight of Armature (kg): 1.81464
Weight of Permanent Magnet (kg): 0.444
Weight of Armature Core Steel (kg): 3.60202
Weight of Rotor Core Steel (kg): 2.48942
Total Net Weight (kg): 8.35008
Consumption of Armature Core Steel (kg): 8.4408
Consumption of Rotor Core Steel (kg): 3.65304

4.6 *Steady state parameters*

The steady state parameters have been calculated after optimizing the design.

Stator Winding Factor: 0.965926
D-Axis Reactive Inductance Lad (H):0.000292119
Q-Axis Reactive Inductance Laq (H):0.00116123
D-Axis Inductance L1 + Lad (H): 0.000433385
Q-Axis Inductance L1 + Laq (H): 0.0013025
Armature Leakage Inductance L1 (H): 0.000141266
Slot Leakage Inductance Ls1 (H): 0.00010566
End Leakage Inductance Le1 (H): 1.43371e-05
Harmonic Leakage Inductance Ld1 (H): 2.12689e-05
Zero-Sequence Inductance L0 (H): 0.000141266
Armature Phase Resistance R1 (H): 0.0430794
Armature Phase Resistance at 20C (ohm): 0.0354363

5. Performance analysis

1) *Effect of stack length on efficiency, no-load current and torque*.
The performance of the proposed machine is analyzed for different stack lengths. It is observed that, for the stack length of 100 mm the efficiency, no-load and torque angle are as per the requirements (table 1).
2) *Effect of back iron on efficiency, no-load current and torque*.
From the analysis, it is observed that the back iron should be sufficient for the dissipation of heat and flux linkages (table 2).
3) *Effect of top tooth width on efficiency, no-load current and torque*.
The top tooth width should be sufficient for the flux linkages and minimizing the no-load current. It is finalized by analyzing the machine for different stator slot dimensions (table 3).
4) *Effect of rotor structure on efficiency, no-load current and torque.*
The PMSM is analyzed for different rotor structures and observed the effect on efficiency, no-load current and torque angle. The bridge type rotor structure is the best for the better performance of the motor (table 4).

6. Optimized design and analysis

After the observation of the motor for the different stack length, back iron, top tooth width and rotor structure and also the steady state parameters, the design is optimized and the results are obtained (table 5).

Table 5. Optimized design sheet of PMSM.

Specification	Value
Operation Type:	Motor
Mechanical Load Type	Constant Power
Power Output (kW)	3
Voltage (V)	48
Number of Poles	6
Speed (rpm)	3000
Stator slots No.	36
OD of Stator (mm)	126
ID of Stator (mm)	80
Length of Stator Core (mm)	100
No. of Conductors per slot	6
OD of Rotor (mm)	79
ID of Rotor (mm)	25
Rotor Structure Type	Bridge
Type of Magnet	NdFe 35
Line Current on No-Load (A)	9.29
Input Power on No-Load (W)	66
No-Load Air Gap Flux Density (Tesla)	0.68
Cogging Torque	4.32214e-13
Line Voltage (V)	62.5311
RMS Line Current (A)	37.0823
RMS Phase Current (A)	21.4089
Armature Thermal Load (A^2/mm^3)	67.3226
Specific Electric Loading (A/mm)	18.3993
Total Loss (W)	121.516
Power Output (W)	2996.69
Power Input (W)	3118.21
Efficiency (%)	96.103
Synchronous Speed (rpm)	3000
Rated Torque (N.m)	9.53877
Torque Angle (degree)	28.0899

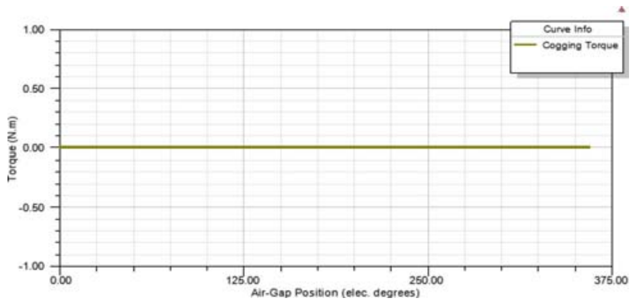

Figure 5. Cogging torque.

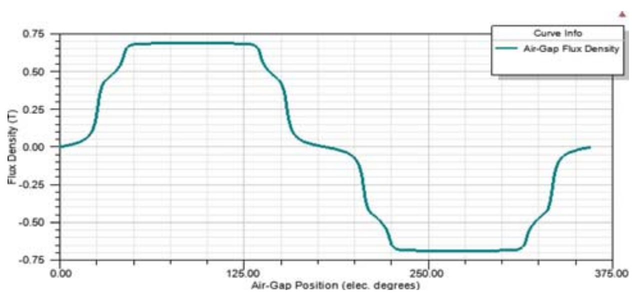

Figure 6. Flux Density in Air gap

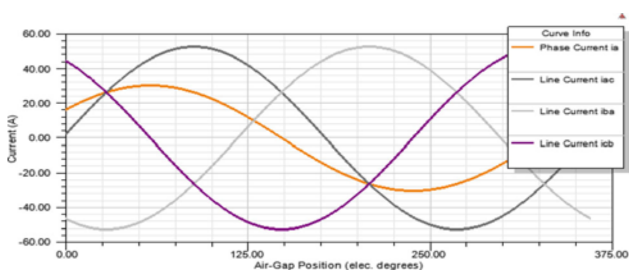

Figure 7. Phase and lone Currents

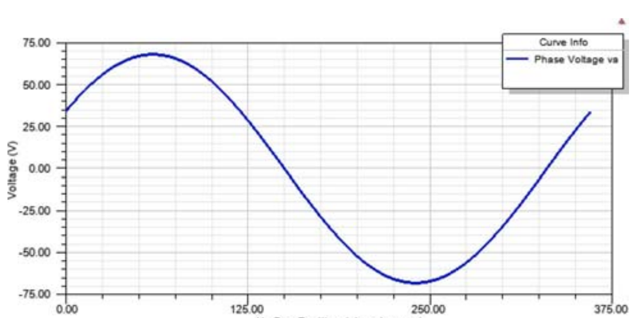

Figure 8. Phase Voltage

The motor performance curves are obtained for different air gap positions. If the slots are skewed by 1 number of slots then cogging torque becomes zero as indicated below figure 5.

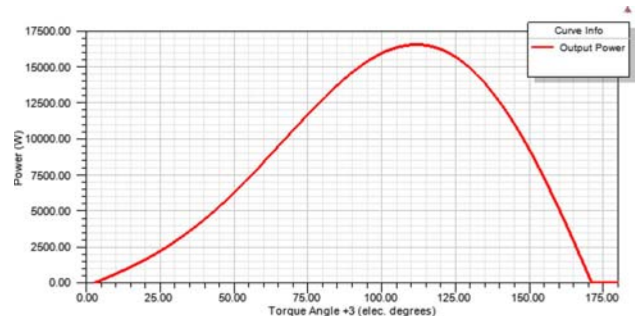

Figure 9. Output Power and Torque Angle Characteristics

The B_{gmax} is also optimized by skewing the slots as presented below in figure 6.

The phase currents and line currents as shown in figure 7 are sinusoidal and indicate the normal working of the motor on full load.

The induced phase voltage as shown in figure 8 is also sinusoidal and it is due to skewing by slot 1.

The Figure 9 indicates the output power and torque angle characteristics which is also satisfactory.

7. Conclusion

The proposed permanent magnet synchronous motor will be having reduced size, constant full load torque, adjustable speed up to rated speed and higher efficiency.

As per the finite element analysis and design calculations, the rating of the motor is 3 kW, 3000 rpm, 48 V, 6 Pole, 150 Hz frequency, rated torque 9.5 N-m, and torque angle 28.08°. Volumetric ratios are (1) armature copper to core = 2.02, (2) armature copper to steel = 0.99 and (3) armature copper to magnet = 6.64.

As per the characteristics of Electric Scooter for constant power application, this motor is the best as per the RMxprt design. The Maxwell 2D and 3D analysis is also in process. The motor is to be fabricated and tested for the said application of constant power.

Robustness of the design for minor variations in dimensions or other variations: The issues related to the design have already been discussed in section 3 of design considerations. To achieve the best performance by the motor, the cogging force, power density and leakage flux need to be controlled by selecting the air gap flux density; motor length and number of poles within the limiting ranges. The variations in dimensions such as stack length, back iron, slot area and rotor structures have discussed in section 5 under performance analysis. Hence, with the minor variations in dimensions and air gap flux density, the performance by the motor would not be much affected and the design would be robust as per the considerations.

The general manufacturing inaccuracies that may occur are: the alignment of the stator and rotor core as per the dimensions, air gap between the stator and rotor, rotor and stator core length, stator slot fill factor and winding layout.

The manufacturing inaccuracies will affect the air gap flux which would not be uniform, flux linkages will also be affected with the difference in core lengths of stator and rotor and hence the back emf will be deviated from the simulation results.

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