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Design and Analysis of PMSM Traction Motor for Passenger Car Applications

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Abstract*: In recent years, owing to the severity of global warming and deduction in petroleum resources quicken the researches to move on sustainable energy resources. Thereby E-mobility has been picturized and fully electric vehicle technology is the major research area nowadays. This paper presents the design methodology of electric traction motor requirement by considering vehicle dynamics and passenger car parameters. Pertaining to the vehicle desired performance, the maximum optimal power is computed. Followed by that power, torque Vs speed profile is determined and the same is compared with the urban and extra-urban drive cycle to estimate the average power and torque. Then the Interior PMSM 2D Finite Element Method (FEM) analysis is planned to carry out with the geometries obtained from analytical calculations for two different slot-pole combinations. The performance differences such as torque Vs speed profile, No-load Back EMF and torque ripple are investigated.

***Keywords*: Drive cycle analysis, Electric vehicles, FEM analysis, Interior PMSM machines, NEDC drive cycle, Power train design, Slot-Pole combinations, Traction motor and Vehicle dynamics.**

I. INTRODUCTION

With the tendency of increasing energy conservation, depletion of global warming, deduced dependency on oil resources, curtailment of conventional IC engines, Electric vehicle technology has been progressively improved in recent days to rely on sustainable energy resources. Electric power train design is a major challenging area in electric vehicle design. To get more accuracy in powertrain while running, the design of electric traction motor should be very optimal. To formulate the electric traction motor specifications, vehicle dynamics is a crucial factor. Also Permanent magnet machines have been the best choice for electric vehicle among that Interior PMSM has many features such as high torque density and starting torque, supplemented reluctance torque constant power over wide speed range, and improved field-weakening capability makes the machine well suited for traction drive of electric vehicle.

Based on research in hatchback passenger car, this paper provides the methodology for identifying the power and torque requirement of electric traction motors by considering vehicle dynamics and vehicle parameters. Also Drive cycle analysis is carried out with the vehicle requirements. The continuous operating range in terms of torque and power is estimated by drive cycle analysis. Followed by that 2D FEM analysis of Interior PMSM machine is performed for two different slot-pole combinations and the torque, power Vs speed profile is computed and the same is compared with the torque profile obtained from requirement design. Moreover torque ripple and back EMF harmonics are also studied.

II. VEHICLE DYNAMICS

The fundamental aspect of vehicle design involves basic principle of physics and mainly Newton's second law of motion. The vehicle motion is completely analyzed by the road load forces. The road load consists of mainly four forces [1] which are Aerodynamic, Rolling Resistance, Gradient and Acceleration force. The net load forces determine the optimal power requirement of the traction motor.

A. Aerodynamic Force

Aerodynamic force is defined as the forcewhich acts on the body of the vehicleto resist its motion when it is travelling through air at a particular speed. It comprises of three drag forces: the skin drag force, normal pressure drag and induced drag. The aerodynamic drag force ($\mathrm{F_{aero}}$) is expressed as [5]

$$\mathrm{F_{aero}} = \frac{1}{2}\,\rho\,A\,\mathrm{C_d V^2} \qquad (1)$$

Where aerodynamic drag coefficient (C_d) is normally 0.2-0.3 for passenger car,frontal area (A) in m^2 calculated from width and height of the vehicle, density of air (ρ) in kg/m^3 and velocity of the drive train (V) in m/sec.

B. Rolling Resistance Force

The force occurs due to the deformation on road surface and the wheel is known as rolling resistance force. This resistance forces will be affected by some factors. They arepressure, temperature and material of the tyre and vehicle's speed. The rolling resistance force ($\mathrm{F_{rr}}$) is given by [5]

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$$\mathrm{F_{rr}} = \mu_{\mathrm{rr}}\, m\, g \tag{2}$$

Wheremass of the vehicle (m) in kg,acceleration due to gravity (g) in m/sec^2 and the coefficientof rolling resistance (μ_{rr}) is normally 0.01-0.02 for car tyre on smooth tarmac and concrete road.

C. Gradient Force

When a vehicle goes up a slope, its weight produces a component of force. This force opposes the forward motion. Therefore the force required to climb up the inclined surface, by the vehicle is known as grade climbing force, often called as gradient force ($\mathrm{F_g}$) and is expressed as [5]

$$\mathrm{F_g} = m\, g \sin\theta \tag{3}$$

Where θ is the road angle or angle of inclined surface.

D. Acceleration Force

The force that accelerates the vehicle to move against the resistive forces is known by acceleration force. The force of acceleration ($\mathrm{F_a}$)is given by [5]

$$\mathrm{F_a} = m\, a \tag{4}$$

Where acceleration of the vehicle (a) in m/sec^2.

III. TRACTION MOTOR DESIGN FROM VEHICLE REQUIREMENTS

To obtain optimal power train requirement in terms of power, maximum torque and speed, typical vehicle parameters and its values are considered and vehicle dynamics calculations need to be carried out. The vehicle parameters and requirements for design are listed in Table-I.

Table- I: Typical Vehicle Requirements

Parameters	Values
Vehicle Gross Weight	1500 kg
Vehicle Dimensions	4247*1740*1540 mm
Tyre Specifications	185/70 R14
Rolling Resistance Coefficient	0.01
Drag Coefficient	0.26
Density of Air	1.25 kg/m^3
Acceleration due to gravity	9.81 m/sec^2
Acceleration Constraint	0-60 km/hr in 12 sec
Gear Ratio	10.83
Gear Efficiency	80 %
Base Speed	3000 rpm

A. Maximum Torque Calculation

Based on Newton's second law of motion, the total tractive force ($\mathrm{F_{tractive}}$) needed at the drive wheel will be the sum of driving resistance force and force of acceleration given by [1]

$$\mathrm{F_{tractive}} = \mathrm{F_{aero}} + \mathrm{F_{rr}} + \mathrm{F_g} + \mathrm{F_a} \tag{5}$$

$$\mathrm{F_{tractive}} = \frac{1}{2}\rho A\, \mathrm{C_d} \mathrm{V}^2 + \mu_{\mathrm{rr}}\, m\, g + mg\sin\theta + ma \tag{6}$$

The above mentioned drive system rating expressed in terms of the wheel'smaximum force which is a function of vehicle velocity in m/sec. The maximum torque ($\mathrm{T_{tractive}}$) required at the wheel is expressed as [1]

$$\mathrm{T_{tractive}} = \mathrm{F_{tractive}} * r \tag{7}$$

Where r is the radius of the tyre in m. Then the intended torque ($\mathrm{T_{motor}}$) and speed ($\mathrm{N_{motor\,speed}}$) of the traction motor is calculated by dividing and the multiplying the total tractive force with the appropriate gear ratio respectively and are given as [6] :

$$\mathrm{N_{motor\,speed}} = G\frac{v}{r}\frac{60}{2\pi} \tag{8}$$

$$\mathrm{T_{motor}} = \frac{\mathrm{F_{tractive}}}{G * \eta_{\mathrm{g}}} * r \tag{9}$$

B. Acceleration Constraint

Vehicle acceleration constraints are normally expressed by duration such as 0 to 60 or 100 km/h. The proposed vehicle has an acceleration constraint of 0-60 km/h in 12 sec. The tractive force at the wheel to reach the desired acceleration is calculated by the expression [1]:

$$\mathrm{F_{tractive}} = \frac{1}{5}\rho A\, \mathrm{C_d} \mathrm{V}^2 + \frac{2}{3}\mu_{\mathrm{rr}}\, m\, g + mg\sin\theta + \frac{1}{2}ma \tag{10}$$

After calculating the tractive force, the motor torque and speed related to this acceleration constraint is calculated using the expressions (8) and (9).

C. Maximum Power Calculation

The maximum power required by the traction motor to deliver at the wheels during higher acceleration i.e., at higher speed is determined by velocity formula. Also iterative process is carried out along with two design points calculated above to estimate the exact speed point at which the maximum power range to be obtained. The velocity expression is given by,

$$V(t_n) = \frac{\mathrm{F\ effective}(t_{n-1})}{mass}(t_n - t_{n-1}) + v(t_{n-1}) \tag{11}$$

Where V is the velocity, F $_{\text{effective}}$ is the effective tractive force, t $_n$ is the nth time and t $_{n\text{-}1}$ is the previous time of n.

From all the calculations, the specifications of the traction motor thus obtained are shown in Table-II.

Table- II: Traction Motor Design Specifications

Parameters	Values
Base Speed	3000 rpm
Maximum Torque	86 Nm

Maximum Power	30 kW
Maximum Speed	7500 rpm

The torque, power Vs speed characteristics obtained from the vehicle dynamics calculation for the speed range of zero to 7500 rpm is shown in Fig. 1. Basically the characteristics have two regions (1) constant torque region and (2) constant power region. The figure depicts that at constant torque region, motor maximum torque is constant and the power is gradually increasing over the speed range of zero to 3000 rpm. At 3000 rpm the motor reaches its rated power output. At constant power region, i.e., beyond 3000 rpm (base speed), motor torque gradually decreases as speed of the vehicle increases and the power

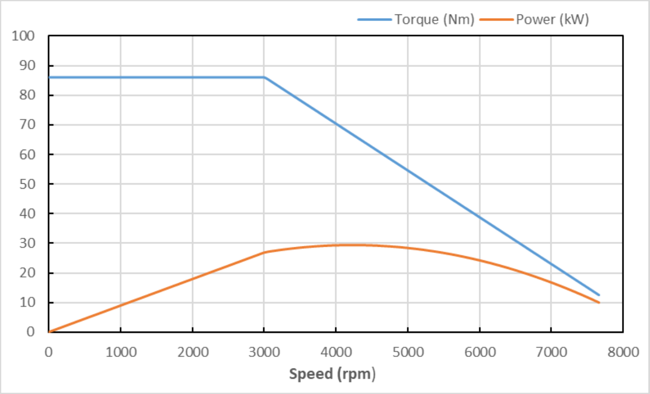

Fig. 1.Power, Torque Vs Speed characteristics from vehicle dynamics

Attains maximum limit and again starts to decrease. But when supplying the motor current by means of controller, the maximum power gets saturated after reaching its maximum.

IV. DRIVE CYCLE ANALYSIS

Another momentous aspect in traction motor design is the computation of average power with standard stop-go driving patterns i.e., so called drive cycle analysis.

It is very challenging to predict the road load force during vehicle speed variations in all the traffic and high speed environments precisely and dynamically. Moreover, drive cycles have been developed to measure and analyze speed variations in the traffic environment.The traction motors specifications like maximum torque, optimal power are also determined dynamically by the drive cycle in which the vehicle operates on. The drive cycle pattern constitutes of:[2] Initial acceleration, Cruising at rated vehicle speed, Cruising at maximum vehicle speed and the Retardation.

Among various drive cycles, New European Drive Cycle (NEDC) is chosen for analysis. NEDC represents the standard drive cycle of four wheelers in Europe and the same is followed in India. NEDC includes urban, which is of 195s durations repeats for four times and extra-urban drive cycles of 400s duration driven only once [4]. The dynamic equations of the vehicle (used in chapter II) and the drive cycle is chosen for velocity and acceleration input.

Drive Cycle analysis is performed. The speed and torque of the electric traction motor with a gear reduction of 10.83 over drive cycle input is shown in Fig. 2. The speed of the vehicle is of zero to 7500 rpm and the maximum torque obtained is not exceeding the theoretical calculated torque over acceleration constraint. The figure depicts that only for a short duration; the machine operates in the maximum torque region.

The speed and power in terms of traction motor speed and power is shown in Fig. 3. This shows that continuous operating range is of 20kW and during extra-urban driving i.e., over high speed ranges, the maximum power delivered from motor is of 30 kW.

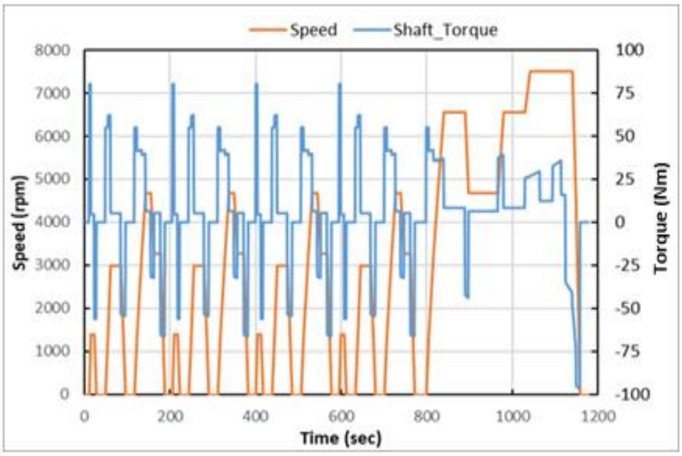

Fig. 2.Torque and Speed Profile over NEDC drive cycle

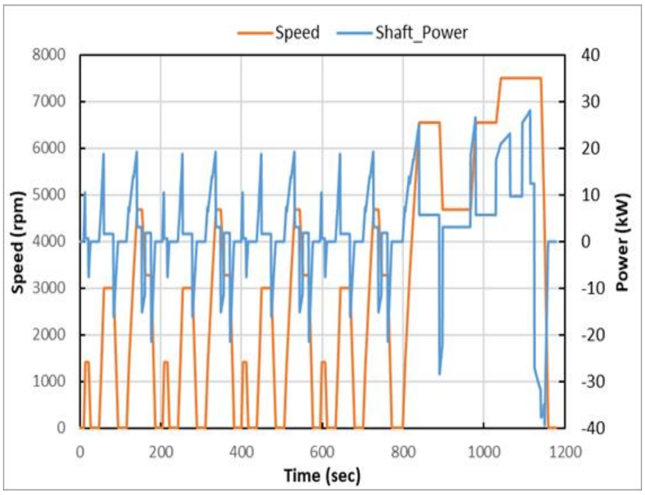

Fig. 3.Power and Speed Profile over NEDC drive cycle

V. SIMULATION DESIGN

The Interior PMSM machine is designed to meet the requirements design shown in Fig 1. The geometries of the machine are calculated using analytical calculations [12] with the motor specifications and are shown in Table-III. The analysis is performed to compare the performance differences of two different slot/polecombinations.

Table-III: Traction Motor Geometries

Parameters	Values	
Stator Outer Diameter	193 mm	
Stator Inner Diameter	118 mm	
Rotor Outer Diameter	116 mm	
Rotor Inner Diameter	40 mm	
Airgap	1 mm	
Stack Length	86 mm	
Number of Slots / Poles	18/8	18/10
Slot Depth	30 mm	
Tooth Width	9.4 mm	
Magnet Width	30 mm	27 mm
Magnet Height	8 mm	6 mm

The motor 2D model and mesh model of two different slot-pole combinations are developed using FEMAG software and are presented in Fig. 4 and Fig. 5.

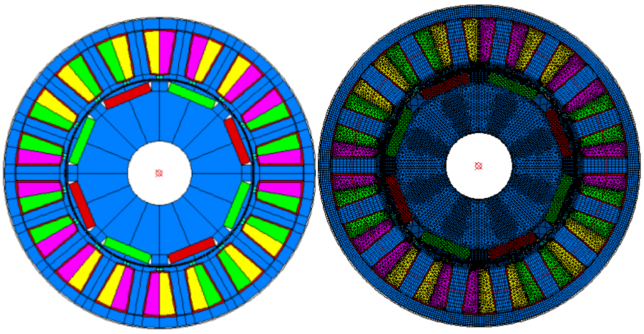
(a) (b)

Fig. 4.(a) Motor model and (b) Mesh model of 18/8 slot-poleInterior PMSM machine

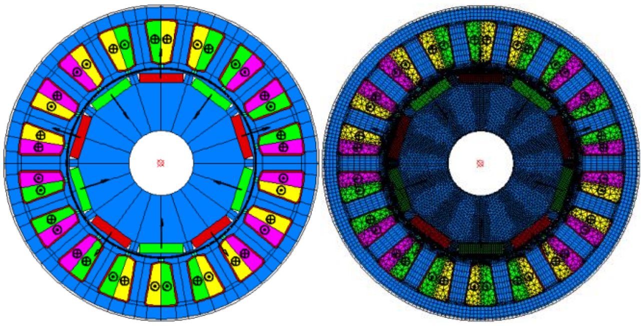
(a) (b)

Fig. 5.(a) Motor model and (b) Mesh model of 18/10 slot-poleInterior PMSM machine

The stator winding is concentric double layer winding type. Since for fractional slot, slot/pole/phase is 0.75 and 0.6 for 18/8 and 18/10 slot-pole combinations, it is desirable to have concentric winding [13]. NdFeB35 grade magnet material is used as permanent magnet in rotor with Remanence flux density of 1.1 T and is of flat type. The motor drive inputs of two configurations are same and are shown in Table-IV.

Table-IV: Traction Motor Drive Inputs

Parameters	Values
DC voltage	400 V
Stator peak current	100 A
Excitation type	Sine wave
Connection type	Star

IV. PERFORMNACE CHARACTERISTICS RESULTS

A. Back EMF Analysis:

The 2D FEM analysis is carried out with 18/8 and 18/10 slot-pole combinations of Interior PMSM machine. The simulation is performed under no load condition and the induced emf is obtained. The induced back EMF of two slot/pole combinations is shown in Fig. 6. This depicts that the back EMF is of appropriate sinusoidal in 18/10 slot-pole combination compared to 18/8 slot-pole combinations as increased poles diminishes the distortion in back EMF.

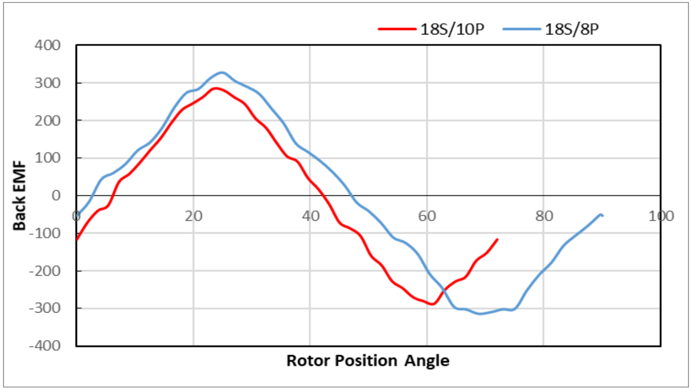

Fig. 6.No-Load Back EMF waveform of Interior PMSM machine

The harmonic content in the induced back EMFs are depicted in Fig. 7. This describes that the odd order harmonic content are higher in 18/8 slot-pole combination compared to 18/10 slot-pole combination. If third order harmonics are completely eliminated then the appropriate sinusoidal waveform will be obtained [13].

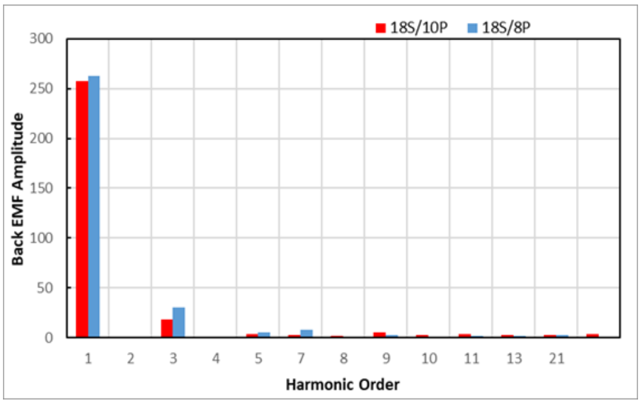

Fig. 7.Harmonic Content in Back EMF Waveform

B. Torque Ripple analysis:

Torque ripple is basically peak to peak on-load torque. Fig. 8. shows the torque profile of Interior PMSM machine at 3000 rpm. However the average torque meets the requirement, the torque ripple is higher in 18/8 slot/pole than the 18/10 slot/pole combinations. This shows that torque ripple becomes small as LCM of slot-pole increases. Also to reduce torque ripple further, the harmonic content in induced EMF need to be mitigated as much as possible [13]. The torque ripple percentage is calculated based on maximum and minimum torque ripple and average torque [14].

Fig. 8.Comparison of Torque Profile at 3000 rpm

C. Torque Vs Speed Characteristics Analysis:

The traction motor is analyzed over the entire speed range from zero to 7500 rpm. The torque, power Vs speed profile of 18/10 slot-pole combinations of Interior PMSM machine since it has better sinusoidal back EMF and reduced torque ripple is shown in Fig. 9. The motor maximum torque is of 86.68 Nm at zero to 2800 rpm and the torque gradually starts to decrease as the speed increases. At base speed i.e., 3000 rpm, the machine voltage reaches the maximum level and becomes constant. The maximum power is obtained at 4000 rpm and is maintained constant.

Field weakening is achieved beyond base speed, current angle (δ) starts to increase, the I_d current also starts increasing in negative direction and I_q current starts decreasing as per the relation:

$$I_q = I_s \cos(\delta)\ ; \quad I_d = -I_s \sin\ (\delta) \qquad (12)$$

Where I is the stator peak current, I_q is the d axis current and I_q is the q axis current. So that back EMF is reduced in the constant power region as speed increases. The figure shows that it meets the vehicle requirements at maximum torque and maximum power.

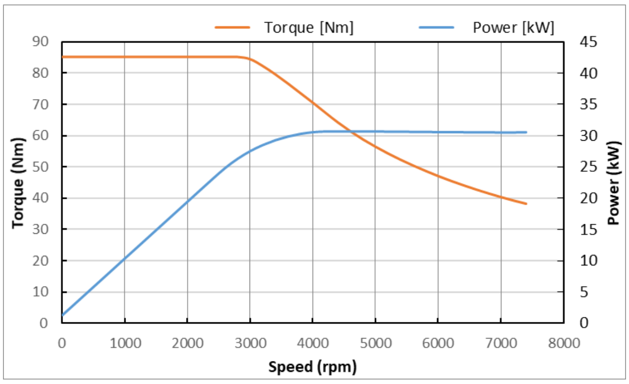

Fig. 9.Torque, Power Vs Speed profile of Interior PMSM machine

V. CONCLUSION

Above work highlights the design methodology of electric traction motor requirements by considering vehicle dynamics and typical vehicle requirements. The maximum optimal power, maximum torque requirement and torque vs speed profile are calculated. The average torque and average power need to be delivered in continuous operating range by traction motor are computed over the drive cycle. The induced back EMF under no-load, torque ripple and torque vs speed profile performances are analyzed by FEM analysis for two different slot-pole combinations. Henceforth the 18/10 slot-pole combination of Interior PMSM has reduced torque ripple, better sinusoidal waveform compared to 18/8 slot-pole combination. To reduce the ripple content in torque and to eliminate the harmonic order inback EMF further, changes in the geometries, V shape magnets and modification in rotor shapes are analyzed for further investigations.

REFERENCES

1. AbdenourAbdelli, Fabrice Le Berr and RaoufBenlamine, “Efficient Design Methodology of an All-Electric Vehicle Powertrain using Multi-Objective Genetic Optimization Algorithm”, *SAE International,2013.S*
2. BekheiraTabbache, SofianeDjebarri, AbdelazizKheloui, Mohamed Benbouzid, “A Power PresizingMethodology for Electric Vehicle Traction Motors”,*International Review on Modeling and Simulations*, 2013, 6 (1), pp.29-32.
3. Amir Ahmed, DikkiD.Bhutia, “Propulsion System Design and Sizing of an Electric Vehicle”, *International Journal of Electronics and Electrical Engineering*, Vol.3, No.1, February, 2015.
4. VesaRuuskanen, JanneNerg, Marko Rilla, and JuhaPyrhonen, “Iron Loss Analysis of the Permanent-Magnet Synchronous Machine Based on Finite-Element Analysis Over the Electrical Vehicle Drive*”, IEEE Transactions On Industrial Electronics*, VOL 63, NO. 7, JULY 2016.
5. Thomas D. Gillespie, “Fundamentals of Vehicle Dynamics”, 1st ed. *Society of Automotive Engineers*, 1992.
6. Emma ArfaGrunditz and TorbjornThiringer, “Electric Vehicle Acceleration Performance and Motor Drive Cycle Energy Efficiency Trade-Off”, *13th International Conference on Electrical Machines*, 2018.
7. Gilsu Choi and T.M.Jahns, “Design of Electric Machines for Electric Vehicles Based on Driving Schedules*”, International Electric Machines and Drives Conference*, 2013.
8. *M. Ehsani, “Modern Electric, Hybrid Electric and Fuel Cell Vehicles: Fundamentals, Theory and Design”, CRC Press*, 2005.
9. Fu Rong, Dou Manfeng, “Optimization Design and Analysis of a 30kW Interior Permanent Magnet Synchronous Motor Used in Electric Vehicles”, *15th International Conference on Electrical Machines and Systems*, 2012.

10. C. M. Siguimoto, N. Sadowski, M. V. F. Luz, C.A.Cezario, “Design and Analysis of Interior Permanent Magnet Synchronous Motors with Optimized Performance”, *International Conference on Electrical Machines*, 2008.
11. J.R.Hendershot and T.J.E Miller, “Design of Brushless Permanent Magnet Machines”, 2010.
12. D. Hanselman, “Brushless Permanent-Magnet Motor Design”, 1st ed. New York, NY, USA: McGraw-Hill, May 1994.
13. Anyuan Chen and Robert Nilssen, “Harmonic Analysis and Comparison of the Back EMFs of Four Permanent Magnet Machines with Different Winding Arrangements”, International Conference on Electrical Machines and Systems, 2008.
14. P. Sethupathi and N. Senthilnathan, “Comparative Analysis of Line-Start Permanent Magnet Synchronous Motor and Squirrel Cage Induction Motor under Customary Power Quality Indices”, Springer-Verlag Electrical Engineering, 2020.

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