

# **Low voltage & low cost Interior Permanent Magnet (IPM) Motor for Indian EV applications**

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## **Abstract**

Interior Permanent Magnet (IPM) motors are strengthening its candidature as traction motor in Electric Vehicles (EV) because of their advantages like high power density, extended field weakening and high efficiency. Being a cost competitive market, Indian EVs cannot afford utilization of large amounts of noble materials like rare earth permanent magnets in traction motors. This paper proposes a design methodology for optimizing the reluctance torque component in order to minimize rare-earth permanent magnet material utilization for improved performance and minimization of torque ripple & cogging torque. Being a high speed motor, structural design considerations and optimization also included in the design process. Vehicle level performance and production cost comparison of proposed IPM motor against conventional low voltage Induction motor also explained. Complete design and optimization of IPM motor was done using 2D Finite Element Analysis (FEA). The vehicle simulation results confirmed extended range and improved dynamic performance with IPM motor for low cost Indian EV application.

*Key Words: Interior Permanent Magnet Motor, Electric Vehicle, low voltage system, Rare-Earth Permanent Magnets, Finite Element Analysis*

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## **1 Introduction**

Electric vehicles gained lot of interest and momentum in recent years to address the concerns associated with global warming and energy crisis. Most of the automotive OEMs are making huge investments to come up with best possible solution to address the above said issues. Since electric motor is the main driving unit in EVs, there is lot of research going on for identifying better candidate electric motor as a traction motor among the lot. [1] Interior Permanent Magnet (IPM) motors are strengthening its candidature as traction motor in Electric Vehicles (EV) because of their advantages like high power density, extended field weakening and high efficiency. [2] Performance of IPM motor highly depends on rare earth magnets, which are highly instable in terms of cost & sourcing monopoly. [3] This paper explains the design methodology to reduce the rare earth material content by optimizing the reluctance torque. Performance comparisons has been made against conventional induction motor for low voltage and low cost Indian EV application.

## 2 Specifications

Torque and power requirements for EV traction motor are quite different from the conventional engine requirements. Traction motor requirement specifications are derived from vehicle level requirements to meet acceleration, maximum speed, gradability etc. Required specifications of traction motor for Indian urban drive cycle based on existing conventional vehicle data are shown in Fig. 1.

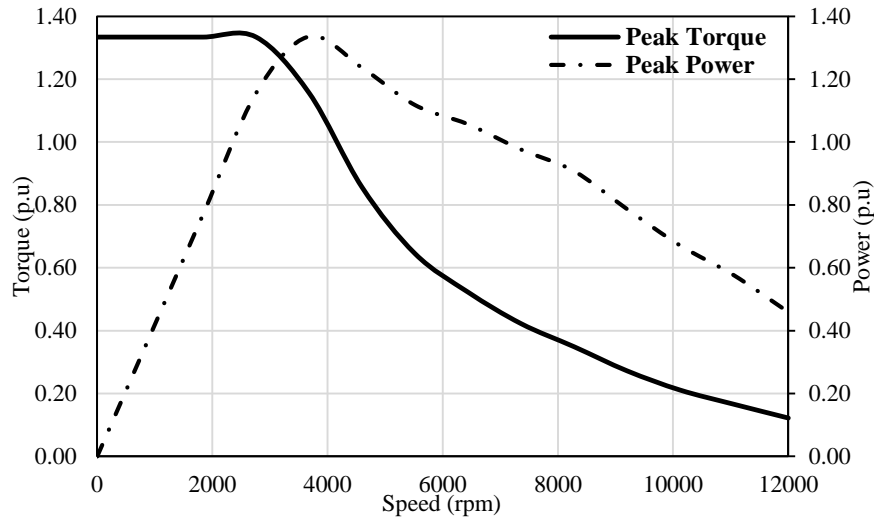


Figure 1: Specifications of IPM motor for Indian electric vehicle

## 3 Design methodology

IPM traction motor design is a multi-objective optimization problem with design variables involved from electromagnetic, mechanical, metallurgy, structural and thermal aspects. [4] Fig. 2 shows the complete design process flow adopted for design of IPM traction motor for Indian EV applications.

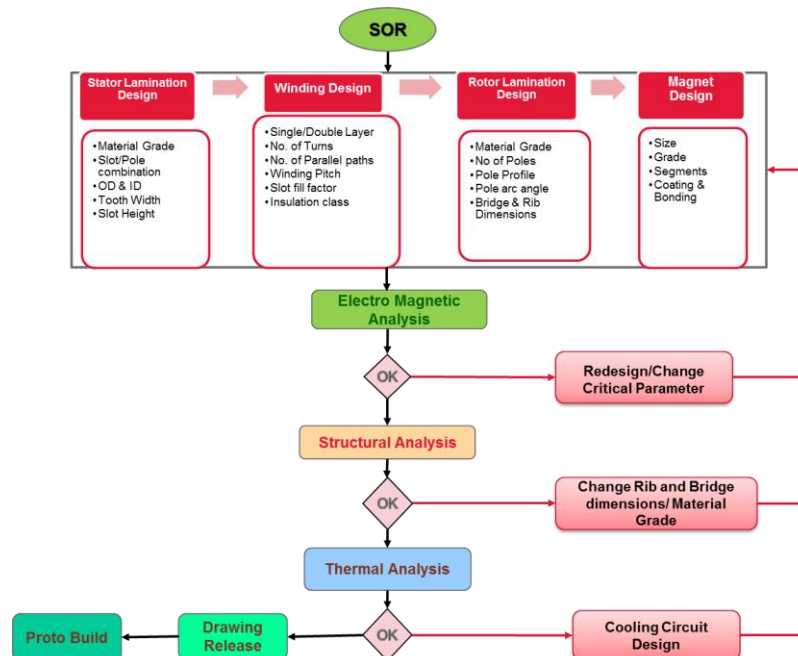


Figure 2: Design process flow of IPM motor

Electromagnetic design and analysis has been carried out using 2D Finite Element Analysis (FEA) with reasonable accuracy. Since the motor is going to operate at higher speeds; stress analysis was performed

on initial rotor laminations to study the deformation patterns and to optimize critical parameters like rib thickness, bridge thickness. Stator lamination cleating specifications has been designed using modal analysis. 1D lumped parameter thermal analysis has been carried out on the final design at continuous and peak power operating conditions for cooling design.

### 3.1 Rotor design optimization

Traction motors are expected to have an extended constant power range up to maximum speed, literature shows that different rotor structures can be used for IPM motor to achieve the same. V shape pole profile has been chosen as the base pole profile and optimization was done to achieve maximum performance.

The electromagnetic torque equation of IPM motor can be expressed as below (1)

$$T_e = \frac{3P}{2} [\lambda I_q + (L_d - L_q) I_d I_q] \quad (1)$$

$$I_{ch} = \frac{\lambda_{pm}}{L_d} \quad (2)$$

$$\zeta = L_q/L_d \quad (3)$$

Whereas  $T_e$  is the electromagnetic torque,  $P$  is the number of pole pairs,  $I_d$  is the direct axis (d-axis) current and  $I_q$  is the quadrature axis (q-axis) current,  $L_d$  &  $L_q$  are d-axis and q-axis inductances,  $\lambda$  is the PM flux linkage,  $I_{ch}$  is the characteristic current of the machine &  $\zeta$  is saliency ratio of the machine.

Design of experiments has been carried to optimize the critical design parameters of IPM rotor for achieving maximum reluctance torque. Optimal design parameters has been chosen considering saliency ratio, PM flux linkage and characteristic current [5] [6].

#### 3.1.1 Design of experiments

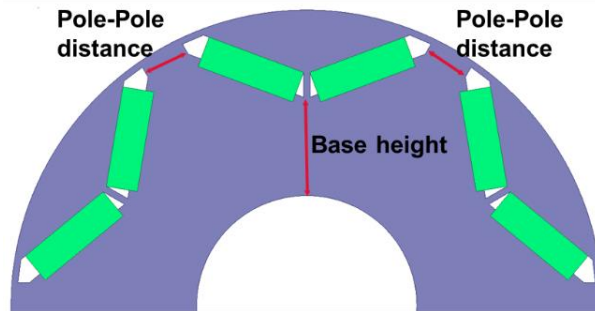


Figure 3: Basic rotor profile of IPM motor

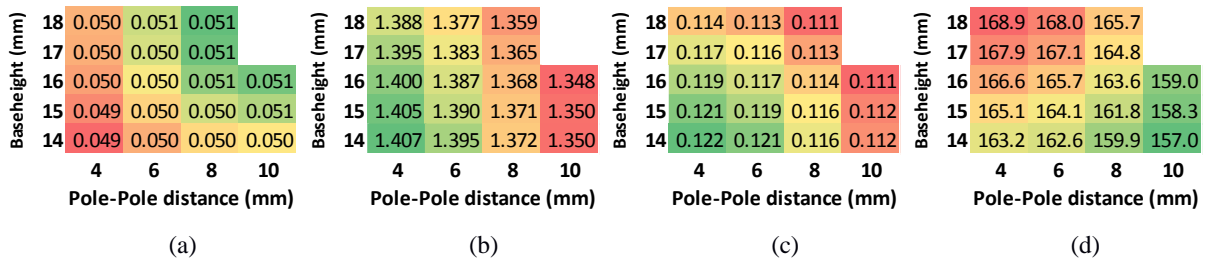


Figure 4. Design of experiments: a) PM flux linkage ( $\lambda$ ); b) Saliency ratio; c)  $L_q-L_q$  (mH); d) Characteristic current

Fig. 3 shows the critical design parameters effecting rotor pole profile thereby influencing the motor performance. IPM machine's magnetic torque component depends on PM flux-linkage  $\lambda$ , reluctance torque component depends on saliency ratio  $\zeta$  and maximum operating speed depends on characteristic current  $I_{ch}$ . Ideally machine can have an infinite speed if  $I_{ch}=I_{rated}$ . Critical design parameters need to optimize considering torque components and characteristic current. Design of experiments with critical design parameters was performed using 2D finite element analysis for performance metrics like PM flux linkage, saliency ratio and characteristic current. Fig. 4 shows the design of experiments carried out on the base design. It is evident that main performance metrics saliency ratio and characteristic current are having contradicting

design parameters for maximum performance. Since saliency ratio is main parameter to reduce rare earth utilization, optimal design parameters of saliency ratio are considered for final design.

## 4 Results and performance comparison

### 4.1 Torque ripple & Cogging torque

Torque ripple and cogging torque indicate the qualitative performance of the IPM machine which will impact the noise and vibrations in the vehicle level performance. Fig. 5(a) shows the torque ripple (pk-pk 3%) and Fig. 5(b) shows the cogging torque (pk-pk 2.5%) of the final design.

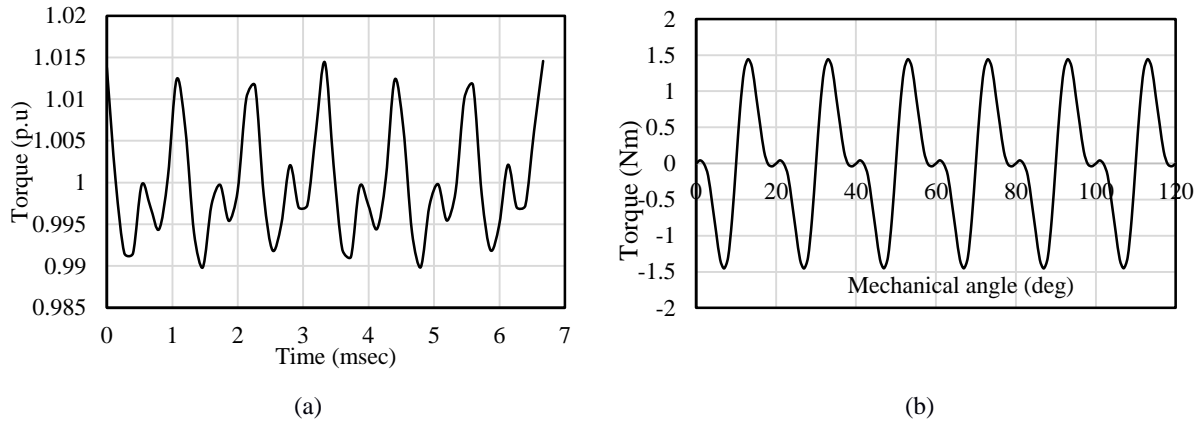


Figure 5. a) Torque ripple; b) Cogging torque

### 4.2 Static torque and efficiency map

Static torque characteristics shows the capability of any machine to deliver the designed peak torque. Fig. 6(a) shows the static torque characteristics of the optimized design. Efficiency of the traction motor impacts the range of the vehicle. Conventional induction motor's efficiency at low speeds is very low and good at high speeds. Fig. 6(b) shows the efficiency map of the IPM motor, which clearly depicts that it is having highest efficiencies at low and medium speeds which is the most frequent operating point of the driving cycle.

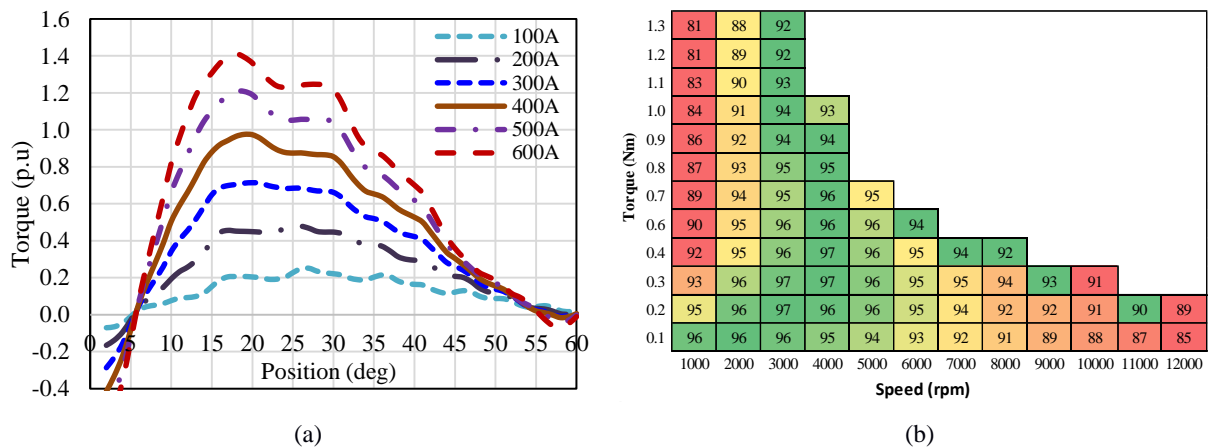


Figure 6. a) Static torque characteristics; b) Efficiency map

### 4.3 Proto build and testing

A 112 frame 36 slot and 6pole IPM motor prototype using rare earth magnets was built. Fig. 7(a) shows the driving end, (b) shows the non-driving end of the finished stator winding shrink fitted in to stator casing. Stator pack was skewed to reduce air-gap harmonics and torque ripple. Stator has been carefully wound to

achieve 50% copper fill for power density enhancement. Fig. 7(c) shows the finished rotor and shaft assembly. Balancing was done using weight removal method. Sin-cos encoder has been used for position sensing.

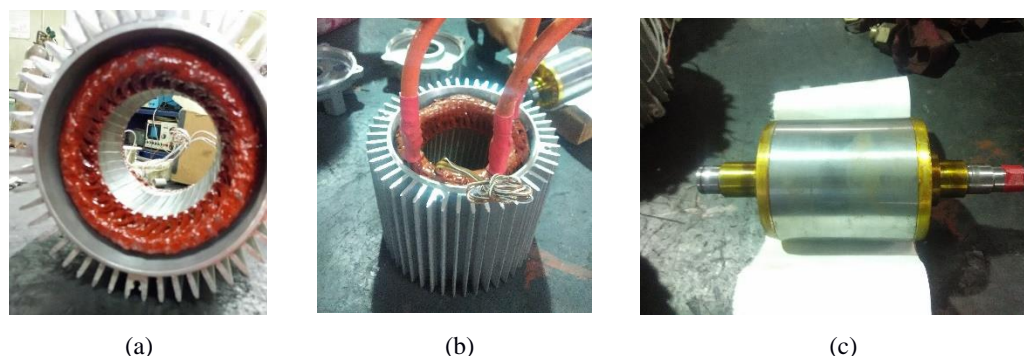


Figure 7. Proto build: a) DE stator; b) NDE stator; c) Rotor

Built motor was tested at component level and vehicle level. Fig. 8(a) shows the IPM motor under test, (b) shows the simulated and measured open circuit voltage. Simulated results are in good agreement with measured results, which indicates the build quality of IPM motor. Fig. 9 shows the simulated and measured torque speed characteristics at vehicle level. IPM motor was mounted on vehicle for performance analysis. Due to vehicle speed limitations testing was limited to 7500rpm. For vehicle level tests IPM motor was characterized using 2D finite element analysis.

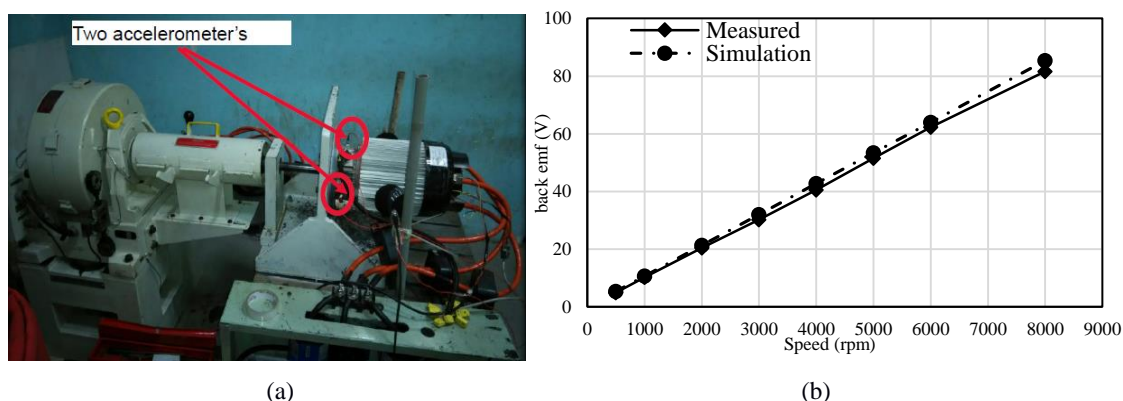


Figure 8. Component level test: a) IPM motor mounted to test bench; b) Open circuit voltage (rms)

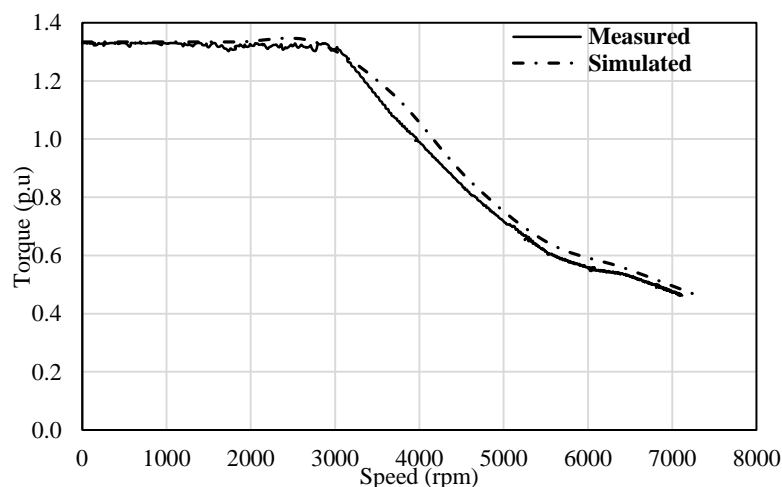


Figure 9. Torque-Speed characteristics

#### 4.4 Performance and production cost comparison

This section explains the IPM motor's performance in comparison to Induction motor at component level and vehicle level. Fig. 10(a) shows the performance comparison of IPM motor with Induction motor including production cost. With optimized rotor lamination to improve reluctance torque, power density of IPM motor increases to 1.5 times of Induction motor power density. Fig. 10(b) shows the impact of IPM motor's performance parameters on vehicle performance in comparison to Induction motor. Since IPM motor is designed for higher torque, higher power and higher speed; gradability, acceleration and maximum speed of the vehicle has been improved in comparison to Induction motor powered vehicle.

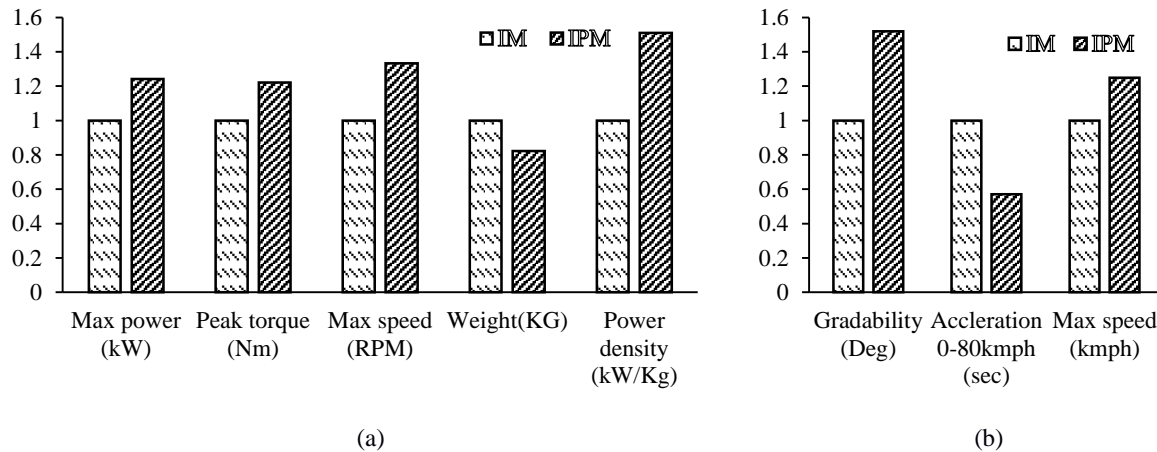


Figure 10. Vehicle level test: a) Performance comparison of IM & IPM; b) Vehicle performance with IM & IPM

Fig. 11 shows the production cost breakup for sub-assemblies of IPM motor and Induction motor. Since both the motors are using 112 frame stator laminations; end casings and fan assembly are standardized. IPM motor being shorter in length; production cost of stator assembly and rotor-shaft assembly is less. Production costs of sensor assembly is slightly higher in case of IPM motors. Primary cost differentiator between IPM motor and Induction motor is rare earth permanent magnets. Total production cost per kW remains almost same for both motors.

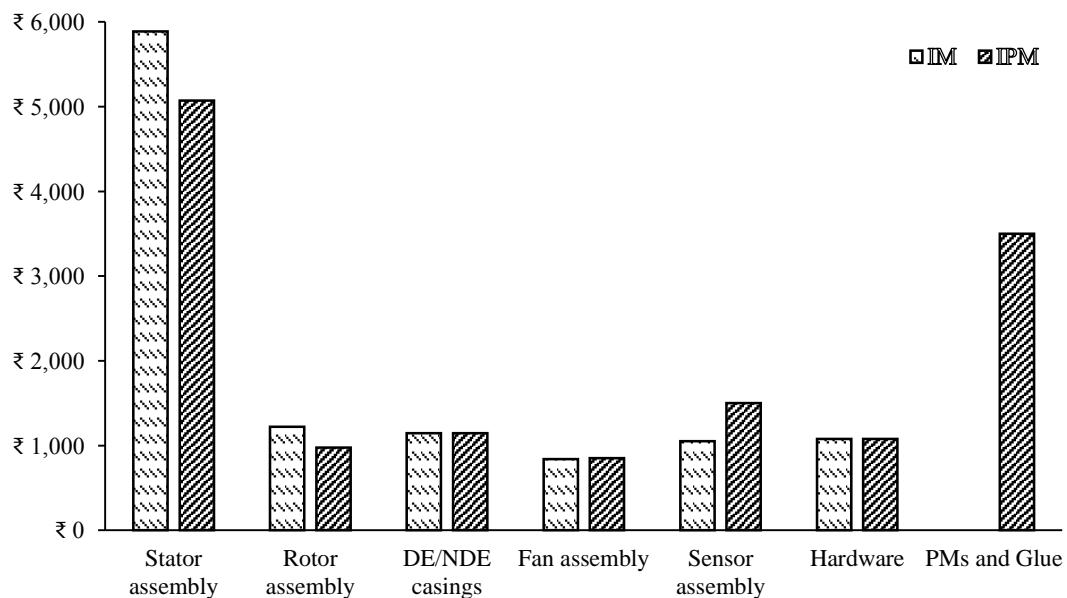


Figure 11. Production cost breakup of IM & IPM

## Conclusions

This paper proposes a design methodology for low voltage and low cost IPM motor for cost competitive Indian EV applications. Torque ripple and cogging torque are minimized to lower values for reducing the noise and vibration in the system level. By optimizing the rotor and magnet size and reluctance component torque component burden on PM torque component has been reduced there by reducing rare earth material content. Component level and vehicle level performance comparison has been made with IPM motor and Induction motor.

## References

- [1] Z. Q. Zhu and C. C. Chan, "Electrical machine topologies and technologies for electric, hybrid, and fuel cell vehicles," 2008 IEEE Vehicle Power and Propulsion Conference, Harbin, 2008, pp. 1-6.
- [2] G. Pellegrino; A. Vagati; B. Boazzo; P. Guglielmi (2012). "Comparison of Induction and PM Synchronous motor drives for EV application including design examples". IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, vol. 48 n. 6, pp. 2322-2332
- [3] Yong-Hoon Kim , Suwoong Lee , Eui-Chun Lee , Bo Ram Cho and Soon-O Kwon, "Comparison of IPM and SPM motors using ferrite magnets for low-voltage traction systems". EVS28, KINTEX, Korea, May3-6, 2015
- [4] Design of Brushless Permanent Magnet Motors. J.R Hundershot J & T.J Miller.
- [5] Report on Toyota/Prius Motor Torque-Capability, Torque-Property, No-Load Back EMF, and Mechanical Losses. J.S.Hsu, C.W.Ayers, C.L.Coomer, R.H.Wiles, ORNL/TM-2004/185, Oak Ridge National Laboratory
- [6] Y. Honda, T. Nakamura, T. Higaki and Y. Takeda, "Motor design considerations and test results of an interior permanent magnet synchronous motor for electric vehicles," Industry Applications Conference, 1997. Thirty-Second IAS Annual Meeting, IAS '97., Conference Record of the 1997 IEEE, New Orleans, LA, 1997, pp. 75-82 vol.1.
- [7] Weiwei Gu & Xiaoyong Zhu & Li Quan & Yi Du, 2015. "Design and Optimization of Permanent Magnet - Brushless Machines for Electric Vehicle Applications," Energies, MDPI, Open Access Journal, vol. 8(12) pages1-13, December.

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Kishor Kumar Bodnapu received the bachelor's degree in electrical engineering from JNT University Hyderabad, India in 2008. He has 9 years of experience in design and development of different traction motors for EV and HEV applications. In Mahindra Electric he is working on design and development of advanced traction motors for EV applications.



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Rajesh Gudivada received the M. Tech. degree in electrical engineering from Indian Institute of Technology Kanpur (IIT K), India in 2009. He has more than 8 years' experience in design and development of advanced motors for traction and industrial applications. He is currently heading the traction motor design and development activities in Mahindra Electric.