Comparative study of traction motor performance in hybrid vehicles

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*Abstract : A study is done to check for the better alternative of the motors that can be used as drive system for a hybrid electric vehicle. Efficiency is an important aspect for the design of drive systems for hybrid electric vehicle drive motors. The study intends to show that the **SRM 24/16** can be designed with a higher efficiency than that of permanent magnet motors for this application. Detailed information about the study is provided. Main intension of this paper is to show that SRMs can be an alternative to replace the commonly used **permanent magnet motors** employed in the power train of HEVs or EVs.*

IndexTerms - SRM 24/16, permanent magnet motors.

I. INTRODUCTION

Efficiency is an important aspect in drive systems for hybrid electric vehicle drive motors. Perhaps motor size and weight is equally or more important than efficiency. The assumption made here is two-fold: firstly, that the SRM 24/16 hold the promise of being as efficient as, or even more than permanent magnet motors in drive application; secondly, that the design for a specific application can help in providing a superior motor.

For vehicle drives, usually, it is viable to choose permanent magnet motors with high performance permanent magnets as it can fulfil the demand of a typical working machine load cycle. These machines can be extremely light weighted and have high efficiency because of their low fundamental reactance and ability to have high pole count. However, the performance prerequisite over a wide speed range can compel some compromise in the design of the motor.

Here, the traction motor used in 2010 Toyota Prius power train is targeted. Motor performances such as torque-speed profile and motor efficiency are discussed and the parameter for the motor geometry of prius traction motor is analyzed. A 24/16 SRM is proposed to achieve the same torque-speed envelope of the IPMSM used in the Prius power train. The volume of the motor without the frame, i.e., stator outer diameter and rotor axial length of the Prius traction motor, is used as the geometric constraint for the 24/16 SRM. The design process of the SRM is also discussed in this paper.

II. OBJECTIVES

i. To study the conventional motor commonly used in the HEVs and EVs.
ii. To obtain an alternative with better moor performance with similar geometric parameters that could be used according to the applications.

III. REQUIREMENTS FOR PERFORMANCE OF THE MOTOR

A standard torque speed envelope requirement that is used in the traction motors for HEV applications is shown in the figure1 [citation]. Operation regions can be differed by the various priority points. Each regions shows specific motor performance requirements. In other words, when the regions are divided in terms of speed, low speed regions gives importance to driver comfort which can be achieved by limiting the torque ripples in an acceptable range and at high speed regions the main objective is to achieve maximum output torque.

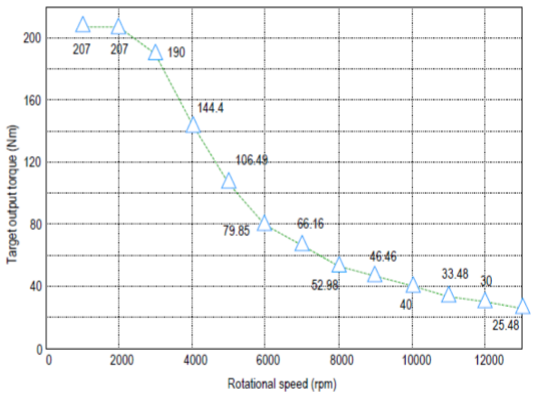

Fig. 1 Target output torque at different speed [4]

The design of the motor used in the 2010 Toyota Prius is such that it has to deliver a peak power of 60 kW with a maximum torque and speed of 207 N-m and a maximum speed of 13,500rpm respectively. This corresponds to a vehicle speed of about 110mph.Table1 emphasizes the major characteristics of the motor used in the 2010 Toyota Prius [3][4].

Parameter	Value
Stator outer diameter [mm]	264
Motor axial length [mm]	108
Stator interior diameter [mm]	161.9
Stator stack length [mm]	50.8
Rotor outer diameter [mm]	160.4
Rotor lamination interior diameter [mm]	51
Rotor stack length [mm]	50.165
Air gap length [mm]	0.73
Lamination thickness [mm]	0.305
Motor casing diameter [mm]	275
Motor casing axial length [mm]	161
Number of stator slots	48
Slot fill factor	0.54
Turns per coil	11
Parallel circuit per phase	N/A
Coils in series per phase	8
Number of wires in parallel	12
Wire size [AWG]	20
Motor peak power rating [kW]	60
Motor peak torque rating [Nm]	207
Rotational speed rating [rpm]	13,500

Table 1 Characteristics of 2010 Prius traction motor [4]

IV. IPMSM SPECIFICATION

IPMSMs employ embedded permanent magnets act as an independent excitation source. They have been generally utilized as the traction motor in electrified power train applications. IPMSM is unique because of the high torque density, high efficiency in a relatively wide operating range, low acoustic noise, and robust performance. The serious issue related to an IPMSM is that it employs permanent magnetic materials and they include rare earth ingredients. These types of motors are capable of achieving high efficiencies in a very narrow operating range.

Permanent magnets that are embedded in the rotor act as the independent excitation source. This helps the motor to achieve a high torque density and a better efficiency at medium and low speeds.

Total torque generated is a combination of magnetic and reluctance torques. Magnetic torque is produced due to the tendency of the magnetic flux, between energized stator coils and magnets, to flow in the path of minimum reluctance.

Total torque is given by the equation [4]:

$$T = P_n \lambda_{d,PM} i_q + P_n (L_d - L_q) i_q i_d \qquad ..(1)$$

The 2010 Prius model has a transmission system containing two sets of power split devices. These devices ensure negligible mechanical losses.

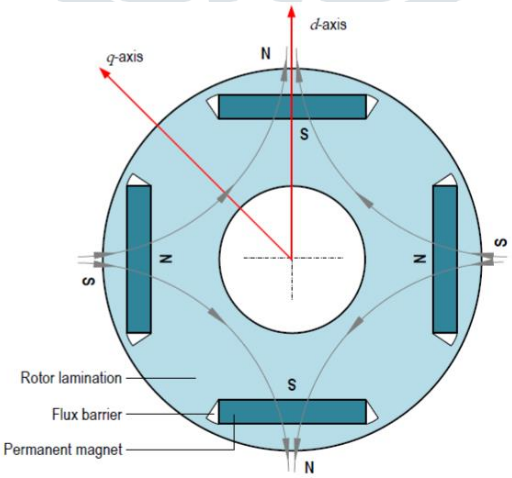

Fig. 2 d-q axis model for typical IPMSM with four embedded permanent magnets [4]

The figure3 represents the torque-speed profile of the IPMSM used in the 2010 Prius model. We can see that the motor can reach a maximum efficiency of 96% without considering the mechanical losses of the machine. But a drop of 7.4% in the efficiency is seen in the 2004 Pius when the mechanical losses are taken into consideration. It is safe to say that the mechanical losses will increase with the increase in the speed of the machine. The highest efficiency range is reached when the motor runs at a speed range of 5000rpm to 7000rpm.

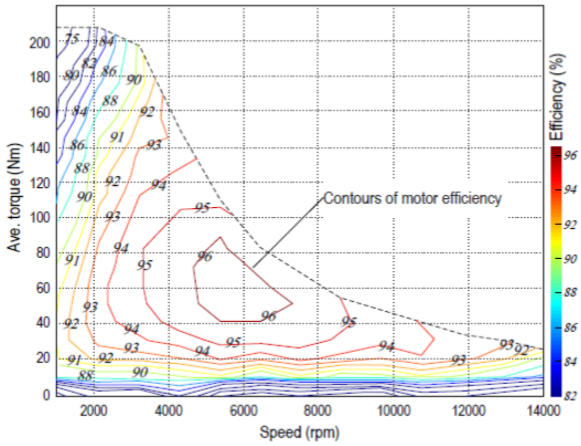

Fig. 3 Torque-speed profile with contours of motor efficiency [4]

V. DESIGN AND SPECIFICTATION OF SRM

The SRM (Switched Reluctance Machine) can be used as the traction motors in the HEVs and EVs. The architecture of an SRM is such that they have salient poles on stator as well as the rotor. Generally there is no winding on the rotor but each of the stator poles have concentrated coils wound around them.

The stator and rotor both employ silicon steel laminations to diminish eddy currents. As compared to the IPMSMs, SRMs can achieve relatively higher efficiencies in a wider range of speeds. They are also capable of operating at higher temperatures as there are no embedded permanent magnets in such motors.

Even though the construction of an SRM is very simple, the design is complex. This id due to the double salient structure of the machine with continuously varying inductance and high saturation of the pole tips. Design optimization can be carried out by electromagnetic finite element method (FEM).

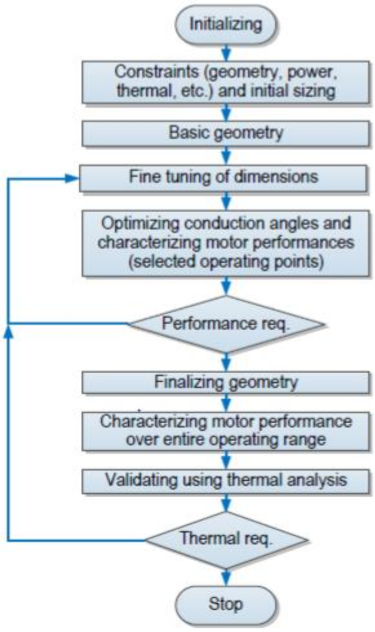

Fig. 4 Process for Geometry Design of SRM [4]

Considering the design process of the SRM given in the figure4 [cite]. The first step of the design process is to initialize the size of the machine and also the geometric constraints of the machine have to be studied and determined accordingly. Since the goal is to obtain a similar performance as that of the 2010 Toyota Prius motor, few parameters like stator outer diameter, slot fill factor, DC-link voltage etc., can be kept same as the IPMSM. Ratings for the DC link voltage and the reference current is taken as 640V and 240A respectively. The design of the SRM has to result in similar performance of both the motors i.e., same peak power, peak torque and speed range of the motors.

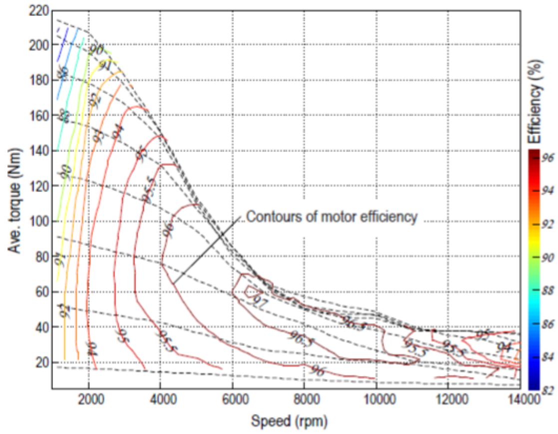

Fig.5 Torque speed profile with contours of motor efficiency of SRM 24/16 [4]

The torque ripple can be reduced in two possible ways, one is to have a high number of rotor poles which will result in a large phase conduction operation which in turn will reduce torque ripples, and another is to increase the no of phases which will increase the overlap between the phase torques and in turn decrease the torque ripples. The latter is a difficult process which can make the motor complicated and also increase the expenses.

Comparing the above figure5 with figure3 we can say that the SRM and the IPMSM used in 2010 Toyota Prius have a similar torque speed characteristics in terms of efficiency. It is seen that the SRM can possibly reach higher efficiency at a larger speed range. The efficiency can reach up to 97% when calculated without including the mechanical losses. We know that the mechanical losses increase with the increase in speed. The 2010 Prius motor shows a peak efficiency at a speed of 4500rpm, whereas the same efficiency is seen in the SRM at a speed of 7500rpm. This efficiency can be seen in a speed range of 6000rpm to 11000rpm which is considerably greater than the machine used in 2010 Toyota Prius.

VI. Conclusion

The motor used in a 2010 Toyota Prius is studied and discussed. It can be proposed that the SRM could be used as an alternative for the IPMSM in the power train of HEVs and EVs. The performance and efficiency of the motor used in the vehicle is analyzed. This analysis is taken into consideration for the designing of the SRM. Design is carried out in such a way that the characteristics of both the motors are similar. From this study we can come to a conclusion that an SRM can successfully replace an IPMSM in the power train system of a hybrid or electric vehicle to have the same performance and efficiency in fact in a better speed range.

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