Design & Comparison of a Conventional and Permanent Magnet based Claw-Pole Machine for Automotive Application

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***Abstract* — This paper presents the design and performance comparison of a conventional claw-pole machine with a permanent magnet based claw-pole machine for automotive application. The magnets are placed in the inter-claw region to decrease the leakage flux and to supply increased magnetic flux in the machine. It has been observed that with the addition of permanent magnets weighing only a few grams, there is a significant increment of more than 22% in output power of the machine. The geometric dimensions of magnets were also varied to verify their effects on performance and it has been observed that with the increase in magnet weight there is a non-linear increment in torque of the machine.**

Keywords — claw-pole; permanent magnet; automotive; motor; alternator; finite element

I. Introduction

Power requirements for automotive applications are increasing day by day with the increase in comfort, safety and luxury in automobiles. With the increase in electric power for various automotive functions, there is also a need of higher fuel efficiency and the automotive applications are moving towards higher voltages of 48 V from erstwhile 12 V systems with increased output power requirements [1]. Generators of output power up to 5 kW and speeds up to 18,000 rpm for these applications are solely dominated, till date, by claw-pole type machines [2]. For mild-hybrid automotive applications, the conventional starter motor and alternator are replaced by an integrated motor-generator set generally known as integrated starter-generator (ISG). The ISG provides its two main functions: (a) starting the internal combustion engine (ICE) by running as inverter driven motor and (b) generating electric power during generator mode by controlled rectification through the inverter. Apart from the main functions, the ISG also provides an auxiliary function of automatic start-stop of ICE during idle standstill, therefore assisting in increased fuel efficiency [2]-[3].

This paper presents design and comparison of a conventional and permanent magnet (PM) based claw-pole machine for mild-hybrid automotive applications. In general, for design and analysis of a belt-driven ISG, the machine design is mainly focused on motoring mode and verifications are done for the generating mode. In this paper the design study for the peak output power of both the machines in motoring mode only has been carried out and comparison of torque vs. speed and power vs. speed for the entire speed range has been evaluated. The generating mode verifications are the scope of future work. It has been observed that the claw-pole machine with PMs provide more than 43% torque in constant torque region and in the range of 22-32% in field weakening or constant power region. The magnet volume is also modified by varying the dimensions of PMs, and it has been observed that there is increment in torque with the increase in magnet weight, but the relationship between torque and PM weight increment is non-linear.

II. Design and Analysis of Claw-Pole Machine using Finite Element Method

A conventional claw-pole machine consists of a 3-phase or multi-phase stator with windings and two forged claw-poles as rotor with ring shaped field coil, fed with direct current (DC) via slip rings and carbon brushes. Fig. 1 shows a conventional claw-pole machine [4]-[5]. In a PM based claw-pole machine, the PMs are placed in the inter-claw region i.e. between the two claw poles, to provide increased magnetic flux and reduce flux leakage between the consequent claw poles [6]-[7]. Research work has also demonstrated that by utilizing Iron-Cobalt (FeCo) soft magnetic materials in the claw-pole alternator, there could be considerable gain in the output performance of the machine [8]. But due to high price of FeCo material the research in [8] shows that by utilizing them only in the rotor core also provides output power increment with less rise in machine cost.

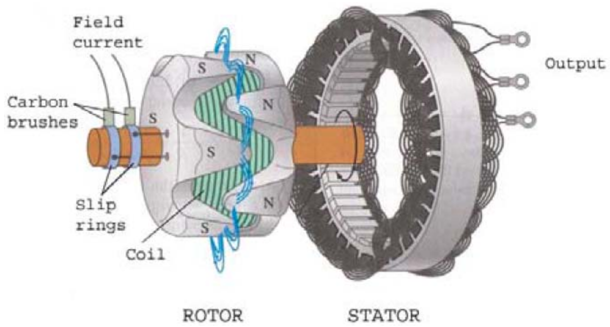

Fig. 1. Conventional claw-pole machine [4]

Literature shows [6] that, with the introduction of PMs in the inter-claw region, there is a torque boost of more than 40% for 42 V DC bus systems with peak output power of around 8 kW for generator operation. Therefore the research carried in this paper is focused on motoring mode during peak power operation with 48 V DC bus mild-hybrid automotive system with speed range from 600 rpm to 18,000 rpm. The performance comparison of both the machines is carried out for the complete speed range taking into account the contant torque and power regions.

The design analysis of the machines has been carried out using classical electrical machine analysis theory using Park's transformation and later finite element (FE) analysis has been investigated to evaluate the machine performance at various speeds [9]. The *dq* transformation equations utilized are as follows [9]:

$$\begin{bmatrix} F_d \\ F_q \\ F_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} F_a \\ F_b \\ F_c \end{bmatrix} \quad (1)$$

where, variable F can represent any of the following, i.e. electromotive force (EMF) e in volts, current (i) in Amps and flux linkage (ψ) in Wb. The θ is angular displacement of the rotor d-axis w.r.t. the a-phase.
The voltage equations are as follows:

$$V_d = R_s i_d + \frac{d\psi_d}{dt} - \omega\psi_q \qquad V_q = R_s i_q + \frac{d\psi_q}{dt} + \omega\psi_d \quad (2)$$

where, V is the voltage in volts, R_s is the stator phase resistance in ohms and ω is the speed in rad/s.
Finally the torque in Nm is as below:

$$T = \frac{m}{2} P\left(\psi_d i_q - \psi_q i_d\right) \quad (3)$$

where, m is the no. of phases and P is the pole pair.

The FE models of both the machines were realized and performance parameters were evaluated by providing appropriate stator and field currents at various speeds for a rotor rotation of one 360° electrical [10]-[11]. In Fig. 2 & Fig. 3 we can observe the magnetic flux density vector plot of the claw-pole rotor without magnets and with magnets respectively. The permanent magnets used in the study are sintered NdFeB with remanent flux density (Br) of 1.3T and coercive field strength of 994 kA/m at 20º C.

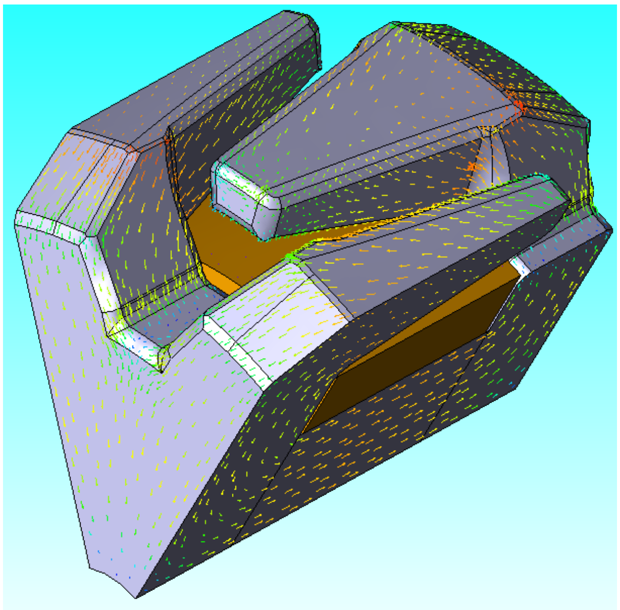

Fig. 2. Magnetic flux density vector plot of claw-pole rotor without magnets

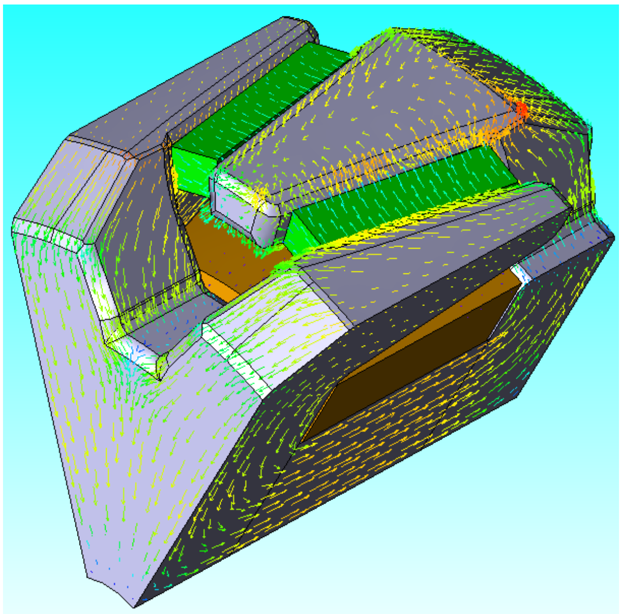

Fig. 3. Magnetic flux density vector plot of claw-pole rotor with magnets

III. SIMULATION RESULTS AND COMPARISON

To obtain the complete torque vs. speed and power vs. speed curve for claw-pole machine, it is very important to optimize the stator current, field current and current angle, so as to obtain the constant torque and power region without exceeding the voltage limit of 48V DC. Multi-objective genetic algorithm methodology was adopted for performance evaluation in the complete speed range.

The objective functions in this analysis were:

(i) To maximize the torque.

(ii) To limit the voltage at 48 V DC.

The optimized d-axis current (I_d), q-axis current (I_q) and field current (I_f) are obtained as a result of the optimization convergence; and this process is repeated for different value of speeds so as to obtain the complete torque vs. speed and power vs. speed curve [12]-[13].

Fig. 4 and Fig. 5 shows the torque vs. speed and power vs. speed curves for both the machines respectively. The results thereafter are calculated in per unit (p.u.) method so as to have quick and straightforward comparison of performance. It can be observed from Fig. 4, in the constant torque region, if 1 p.u. torque is obtained for machine without magnet, then over 1.43p.u. torque is obtained for machine with magnets. Therefore this is an increment of more than 43%. In the constant power region it can be observed that this value reduces, however, it is still in the range of 22-32% increased torque as compared to a machine without magnets. Similarly, it can be observed from Fig. 5 that in the constant power region there is a gain of minimum 22% and maximum 45% in the output power of the machine with magnets as compared to machine without magnets.

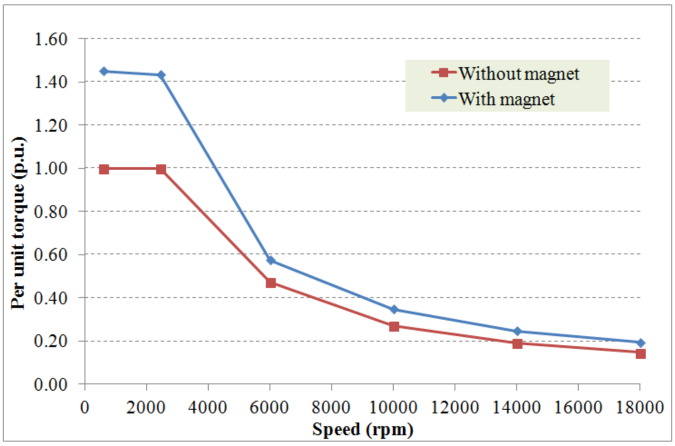

Fig. 4. Torque vs. speed curve for both the machines

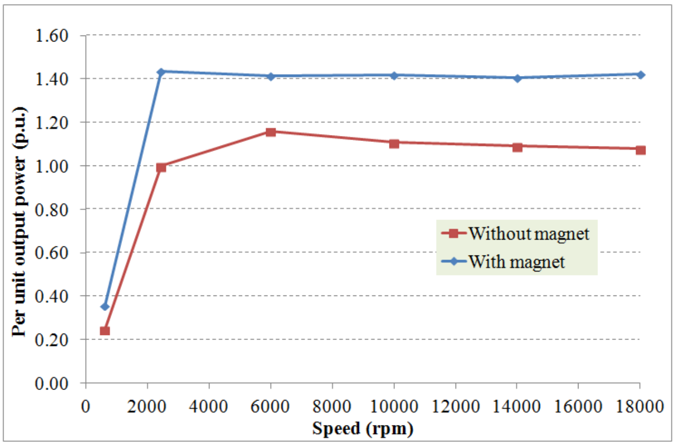

Fig. 5. Power vs. speed curve for both the machines

The objective of this paper is to observe improvements solely due to magnet placement; therefore, the geometry optimization of the claw-poles with magnet is the subject matter of future work. The weight of one PM is 5.64g; hence the total weight of sixteen PMs in the machine with magnets is only 90g. As a result it can be observed that there is a substantial enhancement of more than 22% in the output power of the machine with an addition of only 90g of sixteen magnets.

IV. Effect of Magnet Weight Variation on the Performance

In the following section, effect of variation in magnet weight on the performance of the machine has been evaluated. In section III we observed that with the introduction of PMs in the claw-pole machine there is a notable increment in the output torque of the machine. Therefore, this provided the motivation to investigate the effect on torque of the machine with change in PM weight. As the percentage gain in torque is highest at low speed of 600 rpm, the following studies are carried out by varying the magnet dimensions and calculating the torque at low speed for each case and observing the effects on performance of the machine. Fig. 6 depicts the width, height and length of the magnets, which are varied to obtain different magnet weights.

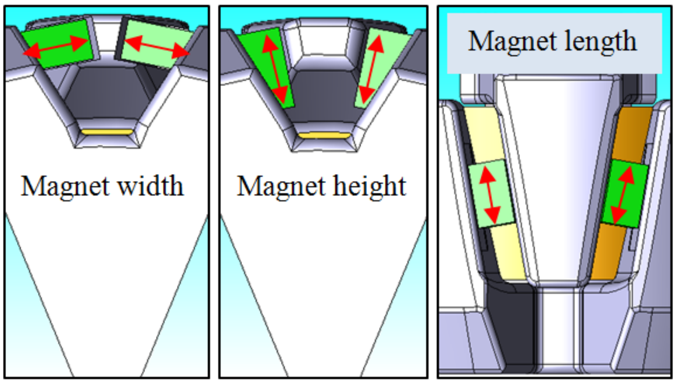

Fig. 6. The width, height and length of magnet utilized for varying the PM weight

A. *Magnet width variation*

As the first step, the width of the PM was varied to change the weight of PM and observe the consequent effects on the low speed torque of the machine. Here on, torque of 1 p.u. value refers to the base condition of 90g of magnet weight and hence the PM width is increased thereafter till the maximum limit of manufacturing tolerances is achieved. Fig. 7 shows the variation of p.u. torque as a function of PM weight by changing the magnet width. It is observed that the torque increases approximately till the weight of PM is 168g and then reduces till the weight of PM is 184g. This is due to the fact that after a certain value of PM width the claw-pole fingers saturate and subsequently there is an overall reduction of flux in the air gap, hence the torque reduces. It can also be observed that there is 5.45% increase in torque from minimum to maximum value by changing the PM width; however there is 103.4% increment in magnet weight from minimum to maximum, hence depicting non-linear relationship between the increase of torque and weight.

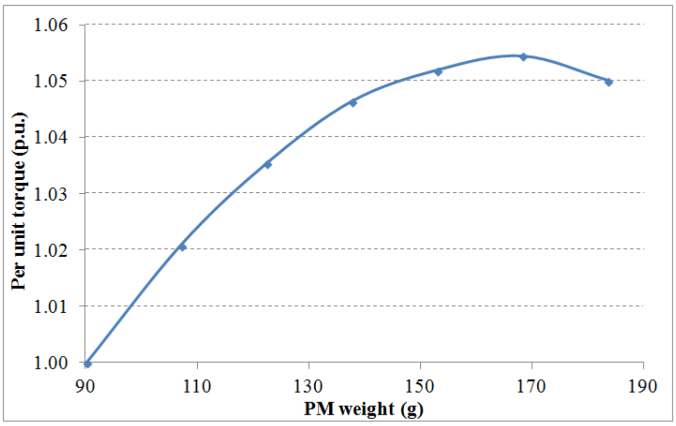

Fig. 7. Variation of torque as a function of PM weight by changing the magnet width

B. *Magnet height variation*

As a second step, the height of the PM was varied to change the weight of PM and observe the consequent effect on the low speed torque of the machine. In this case also the torque of 1 p.u. value refers to the base condition of 90g of magnet weight and hence the PM height is increased from a minimum to a maximum limit till manufacturing tolerances is achieved. Fig. 8 shows the variation of p.u. torque as a function of PM weight by changing the magnet height. Here, it is observed that the torque increases in a polynomial order with increase in PM weight from 54g to 181g. Hence, illustrating that from minimum to maximum value there is an increment in torque of 34% with a large rise in PM weight of 233%.

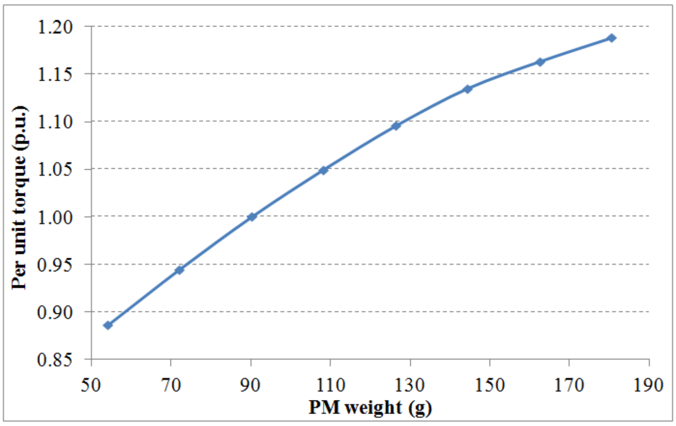

Fig. 8. Variation of torque as a function of PM weight by changing the magnet height

C. Magnet length variation

The length of the PM was varied as the third step to change the weight of PM and observe the consequent effect on the low speed torque of the machine. Similarly in this case the torque of 1 p.u. value refers to the base condition of 90g of magnet weight and hence the PM length is increased from a minimum to a maximum limit till manufacturing tolerances is achieved. Fig. 9 shows the variation of p.u. torque as a function of PM weight by changing the magnet length. Here also it can be observed that the torque increases in a polynomial order with increase in PM weight from 36g to 144g. Therefore, this also shows that the torque increases by 36% from minimum to maximum value, although with a significant rise of almost 300% in PM weight.

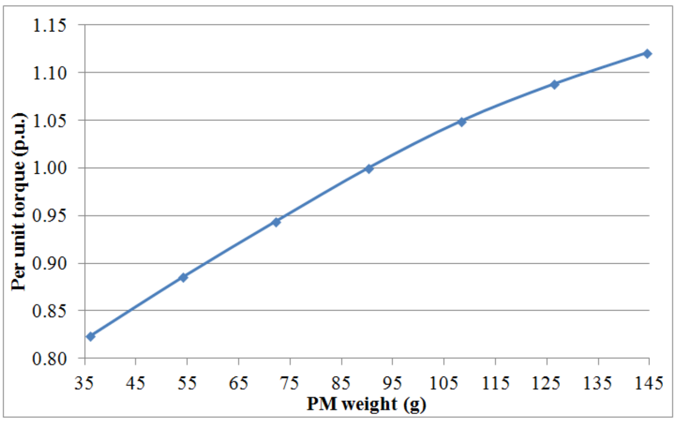

Fig. 9. Variation of torque as a function of PM weight by changing the magnet length

Thus, in continuation to the above three cases; one more scenario is considered where the PM width, height and length are altogether set up to their maximum value. This is done to finally observe the effect on low speed torque by placing maximum PM weight in the machine. Table I shows the total PM weight and p.u. torque of the claw-pole machine with magnets for base model and model with maximum PM width, length and height. It can be observed that the PM weight is increased from 90g to 511g from base model to maximum PM width, length and height model respectively, which translates into 467.78% increment in PM weight. Whereas, the torque is increased from 1 p.u. to 1.39 p.u. from base model to maximum PM width, length and height model respectively, and this translates into 39.35% rise in torque.

TABLE I. COMPARISON OF PM WEIGHT AND P.U. TORQUE BETWEEN BASE MODEL AND MAXIMUM PM WIDTH, LENGTH AND HEIGHT MODEL

	Total PM weight (g)	**Torque (p.u.)**
PM model - base	90	1.00
PM model - maximum width, length & height of PMs	511	1.39
Percentage (%)	467.78	39.35

As a result, from all the above cases it can be observed that the percentage augmentation in torque is comparatively smaller than the percentage increase in PM weight, hence representing non-linear relationship between PM weight and torque increment. This is primarily due to the geometry of claw-pole machine and PM placements in it, since the main role of PM is to reduce leakage flux and assist main flux produced by the rotor DC coil. Thus, optimization of magnet weight with respect to optimum performance of machine is one of the important design criteria in claw-pole machines.

V. CONCLUSION

In this paper it has be illustrated that there is a considerable torque and power boost of more than 43% in constant torque region and around 22-32% in the constant power region with the introduction of PMs in the inter-claw region of the claw-pole machine. With the placement of only 90g of total magnet weight in the machine we perceive a considerable gain in torque, hence improving output power of the claw-pole machine. This translates into significant power to weight amplification of the machine which is one of the main advantages for mild-hybrid automotive application. It has also been observed that because of claw-pole geometry of the rotor and PM placements in inter-claw region; large PM weight increment transforms into small percentage rise in torque of the machine, thus corresponding to a non-linear correlation between PM weight and torque.

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