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AN IPM MACHINE WITH SEGMENTED MAGNET ROTOR FOR INTEGRATED STARTER ALTERNATOR

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ABSTRACT

Ever decreasing fuel source and concern about air pollution by emission of carbon exhaust of car engine make it necessary to develop future automobiles more energy efficient which is forcing the industry to convert many mechanically driven parts to electrically driven ones. Moreover increasing demand for better performance, higher comfort and safety of the passengers etc are also leading to a rise in on board electric power level of present day 2/3 kW to 6/8 kW. In order to deal with the higher power level, the present 14V system needs to be increased up to 42V. The standard of 42V has been decided upon considering many aspects of technical as well economical factors. A key to make this new system economically viable is to develop an integrated starter alternator (ISA) system suitable for common car. The requirement of ISA system poses some interesting machine design constraints. It needs starting torque of 150 Nm from standstill to a minimum engine speed of 150 rpm. On the hand the alternator must deliver 4 to 6 kW of power over a wide range of speed such as 600 to 6000 rpm. Besides, hostile surrounding and scarcity of space inside the car engine also cause some constraints over the machine design. The induction and interior type permanent magnet (IPM) machines both are considered seriously for the ISA application; but both have their limitations. In case of induction machine reducing the size/torque is not very easy, while in permanent magnet machine to achieve flux weakening for wide speed range is a problem. In this paper the design of a new IPM machine especially suitable for ISA application has been investigated. The ISA application is simulated in the Matlab-Simulink environment to check its characteristics and rotor is designed with help of two dimensional Finite Element Method.

1. INTRODUCTION

The low fuel consuming, energy efficient vehicles are need of present time. Higher efficiency also means conversion of some the mechanical system to electrical ones. As a result on board power demands of future cars are rising steadily. The present 14V system will soon be insufficient. A new system of 42 V has been agreed upon considering many aspects of technical as well economical factors. In this system a 36V battery will be used and 42V will be the charging system voltage. By allowing the engine to shut down when not necessary and thus avoid idling, fuel economy can be improved along with corresponding reduction of CO_2 exhaust. The increase in generating requirement will make it comparable with the starting requirement and thereby make the integrated starter alternator system (ISA) more appealing. However the system will be viable only if the present engine architecture need not be changed much. In last couple of decades, many research activities have been seen for development of the ISA system. The interior permanent magnet (IPM) machines are one of the main contenders of ISA application. In this paper an investigation has been made about how suitable a segmented rotor IPM machine is, for directly coupled ISA application.

2. THE ISA SYSTEM

2.1 The Design requirements

The requirement of ISA (Integrated Starter Alternator) system imparts some intriguing design challenges. The machine must start with 150 Nm from standstill up to a minimum engine speed of 150 rpm. The alternator needs to deliver 4 to 6 kW power over a speed range of 600 to 6000 rpm. Moreover, hostile surrounding and scarcity of space inside the car engine along with economy of the system cost,

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bring forth some more constraints over the machine design.

2.2 Coupling arrangements

Two most widely accepted coupling arrangements are directly coupled and belt or gear driven. The first one is very simple; however it will expose the ISA to hostile thermal conditions and length of the machine need to be short to fit in the machine crank shaft. In the belt/gear driven system, the ISA will be placed in the adjacent to the engine drive train. Although such a configuration will remove some of the above mentioned constraints from the physical machine design, higher power requirement will place very heavy demand on the belt/gear system.

2.3 Suitable Machine Types

The induction and interior type permanent magnet (IPM) machines both are considered seriously for the ISA application; but both have their limitations. Reduction of the core length per torque requirement is not very easy in induction machine and there are some stability issues in generating mode. In case of permanent magnet machine, to achieve flux weakening for wide speed range satisfying all other requirements, is one of the main challenges.

3. NEW MACHINE DESIGN

The IPM machine is very efficient for high performance drives. Considering size constraint of the ISA system, pancake type IPM machines seem to be an ideal candidate. T. M. Jahns et al with the collaboration of MIT/Industry Consortium on Advance Automotive Electrical/ Electronic Components and Systems have already developed an optimized design of IPM machine particularly suitable for ISA application [1,2]. In their design, the rotor pole is developed with two layers of permanent magnet material with remnant flux density >0.28T (bonded NdFeB). Inspired by the above design, we are trying to develop another novel IPM machine suitable for ISA application. Since the volume of permanent magnet material is a deciding factor in the total cost of the machine, it is sensible to reduce the magnet volume as much as possible without affecting its performance ability. In our design, rotor magnet pole has only one layer of bonded NdFeB (remnant flux density of 0.46 T). The concept of rotor segment [3] is applied to achieve wider flux weakening range. The optimized stator design of [2], has been considered as a basic stator model. The figure 1 is showing the top view of the machine structure and figure 2 is showing details of one pole. The machine consists of twelve poles, each pole having 6 magnet pieces of varying dimensions. Details of the machine dimensions can be found in the Table 1.

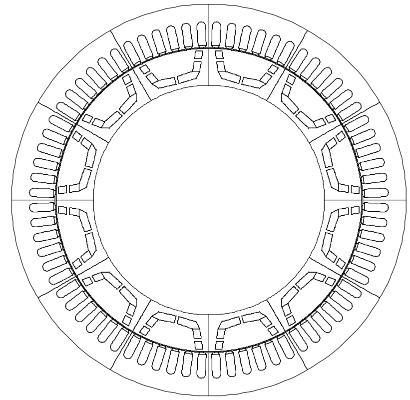

Fig. 1 Top view of the machine structure

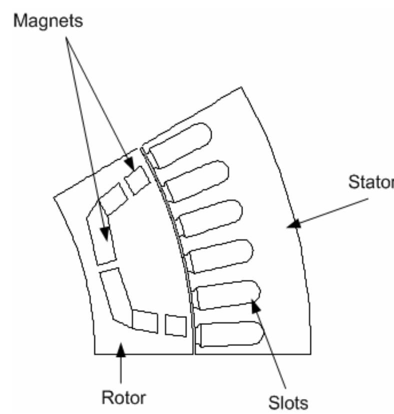

Fig.2 One pole of the machine

4. PARAMETER ESTIMATION

4.1 Magnet flux linkage calculation

In case of single stage power converter, rated terminal voltage of the ISA machine will be solely determined by the DC bus voltage. The maximum allowable level of DC link voltage suggested by the 42V-PowerNet, is 52 V including all the ripples. Thus the required magnet flux linkage can be determined from the permissible level of DC link voltage at the maximum speed using (1) [4].

$$V_{DC} = \sqrt{3}\Psi_{PM}\,\omega_{e\_max} - 2 \times V_{sw} \qquad (1)$$

Where, V_{DC} is maximum Permissible DC voltage, Ψ_{PM} is magnet flux linkage, ω_{e_max} is maximum electrical speed and V_{sw} is voltage drops in converter switches. The voltage induced by the magnet alone at the speed of 6000 r/min, for the machine obtained from Finite Element (FE) analysis, is shown in the figure 3. The condition for optimal flux weakening is,

$$\Psi_{PM} = L_{ds} I_s \qquad (2)$$

Where, $\boldsymbol{L_{ds}}$ is d-axis inductance and $\boldsymbol{I_s}$ is maximum current of the system.

Table1: Dimensions of the Machine

Name	Quantity
Number of Poles	12
Maximum rated speed	6000[r/min]
Stator and rotor core material	Non linear steel
Magnet Remnant Flux Density	0.46[T]
Bridge thickness	2 [mm]
Stator outer Diameter	280[mm]
Core length	60[mm]
Rotor Outer Radius	108.4[mm]
Rotor Inner Radius	82[mm]
Air gap length	60[mm]
Winding Factor	0.9224
Number of series turns per phase	24
Number of slots	72
Thickness of the Magnets	5[mm]
Dimension (b×h) of horizontal magnet piece	12×60 [mm×mm]
Dimension (b×h) of Vertical magnet piece	7× 60[mm×mm]
Magnet span	150 [elect.degrees]

Since the ISA machine has quite large current rating due to the required large starting torque, flux linkage obtained from (1) will be smaller than the optimal value of (2). As seen from figure 3, there will be some harmonics in the induced emf due to the segmented magnet poles.

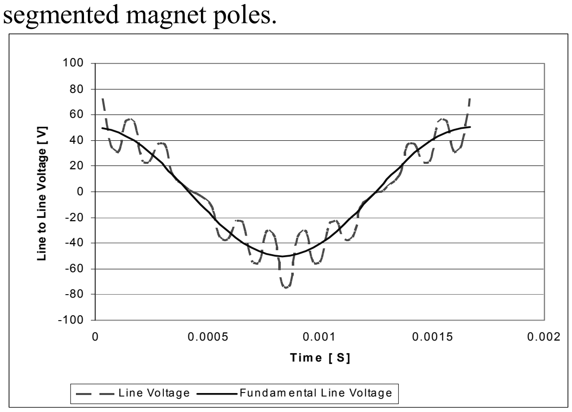

Fig.3 Magnet induced line to line voltage

4.2 Inductances calculation

The Finite Element analysis was used to estimate the inductances. The variations of inductances over the current are shown in fig. 4 and 5. The q axis of the IPM machine is affected by the saturation of the core iron due to the current. Hence L_{qs} is varying with current. In table 2 various parameters of the machine is listed.

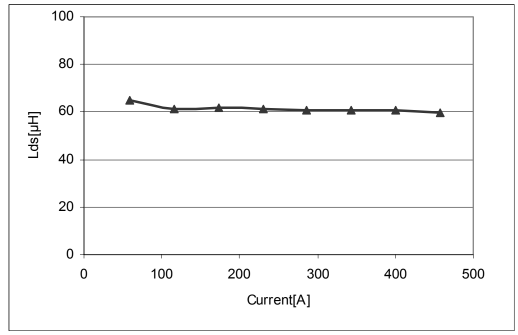

Fig.4 Variation of L_{ds} with current

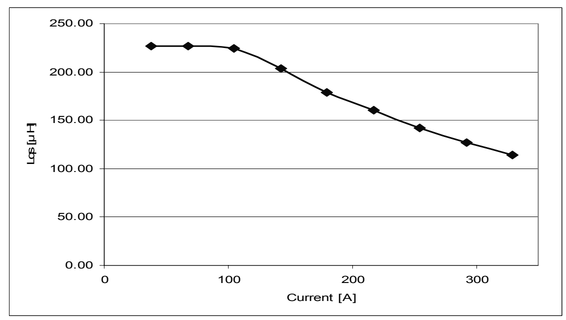

Fig.5 Variation of L_{qs} with current

Table 2: Machine Parameters

Name	Quantity
Base Voltage	19[V]
Stator current at peak torque	327[A]
PM flux linkage	7.68[mWb]
Maximum back emf at 6000 r/min	21[V]
Phase resistance	20.3[mΩ]
d-axis inductance	60.3[µH]
q-axis inductance	138[µH]

5. SIMULATION RESULTS

The block diagram of the ISA system with a vector controller is shown in figure 6. In high performance vector control configuration, reference i_{ds}^* and i_{qs}^* currents are derived from a reference torque command [5]. For the ISA system T_e^* can be derived either from starting toque command during motoring or from DC bus regulator during generation. The starting operation occurs at low speed only, hence the voltage constraint of the system does not affect the system and maximum toque per ampere (MTPA) algorithm can be used to produce the required torque during whole motoring range. The figure 7 is showing the torque speed characteristic of the machine during motoring. The power capability of the machine up to 6000 r/min is shown in figure 8. The peak power capability of the machine is around 8 kW. The figure 9 is showing the regulated DC bus voltage at 1000 r/min.

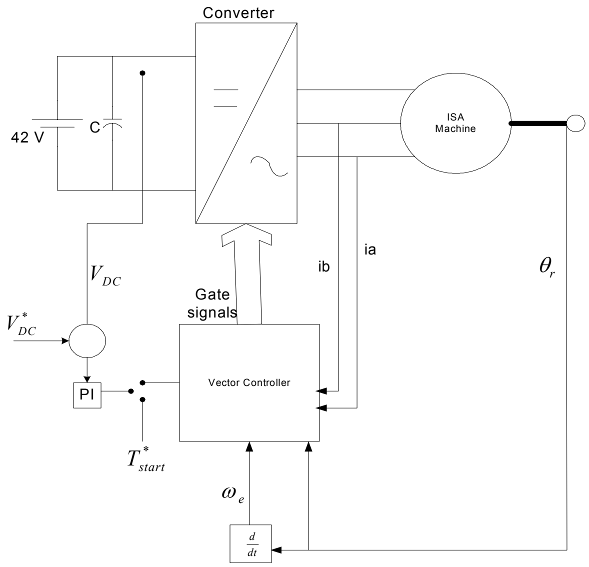

Fig.6 Block Diagram of ISA system

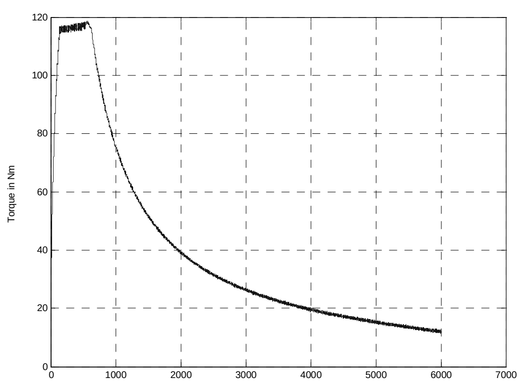

Fig.7 Torque-Speed Characteristics

6. CONCLUSION

In this paper, designing of an IPM machine for ISA application has been presented. The Simulation of the system shows promising results. It has been noticed that for the same rated current (327 A), the produced torque is slightly less than 150 N-m for the segmented design. Hence a slightly higher current rating will be necessary. The DC bus voltage regulation is quiet satisfactory for the wide range of speed operation.

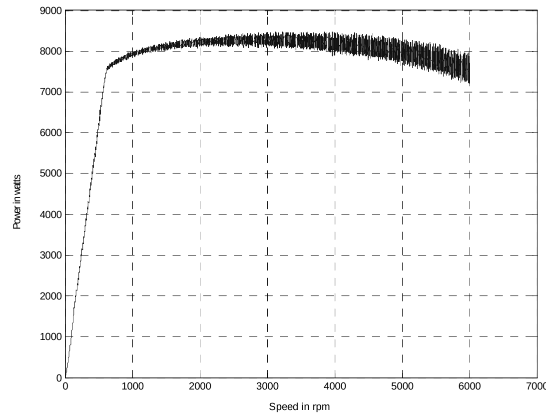

Fig.8. Power Capability

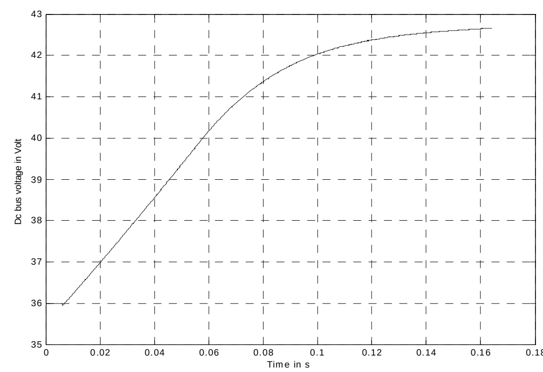

Fig. 9 DC Bus voltage

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