Applied Mechanics and Materials
ISSN: 1662-7482, Vols. 773-774, pp 781-785
doi:10.4028/www.scientific.net/AMM.773-774.781

Submitted: 2014-10-16
Accepted: 2014-12-22
Online: 2015-07-15

Performance Analysis of 12S-10P HEFSM with Various Flux Bridges

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Keywords:, flux switching machine, hybrid excitation, iron flux bridges.

Abstract. Flux switching machine (FSMs) with several advantages of robust rotor structure, high reliability, high efficiency and high torque density have been develop in recent years. Among several types of FSM, HEFSM gives extra advantage at variable flux capabilities suitable for higher load conditions. However, the developed C-Type has a problem of separated stator core which lead to difficulty in manufacturing design as well as flux leakage to the outer stator. In order to solve the problem, iron flux bridges have been introduced to the stator core. Because of that, the separated stator core becomes the single piece of core. In this paper, various topologies of iron flux bridges is introduced and overviewed. Performances of torque at various flux bridge is analyzed and compared. This analysis is verified by Finite Element Analysis (2D-FEA).

Introduction

Commonly, the flux switching machine (FSM) can be categorized into three groups. The first concept of FSM was founded in the middle of 1950's. The categories of FSM are consists of Permanent Magnet Flux Switching Machine (PMFSM), Field Excitation Flux Switching Machine (FEFSM) and Hybrid Excitation Flux Switching Machine (HEFSM). Both PMFSM and FEFSM has only PM and field excitation coil (FEC), respectively as their main flux sources whereas HEFSM combines both PM and FEC as their main flux sources. According to their theory of operation, HEFSM is getting more prominent lately.

HEFSM are those which use two excitation flux sources whereas utilize permanent magnets (PMs) as primary excitation meanwhile field coil excitation as a secondary source. The combination of advantages for both PM machines and wound field synchronous machines becomes goal behind the association of both sources that have been researched over many years. Conventionally, by controlling the armature winding current, PMFSMs can be operated beyond base speed in the flux weakening regions. In addition, the PM flux can also be counteracted by applying negative d-axis current. Besides, it gives the disadvantages of increase in copper loss and also reduced the efficiency. In addition, the other disadvantages are can reduced the power capability and also possible irreversible demagnetization of the PMs. HEFSM have the potential to improve the flux weakening and flux enhancing performance and efficiency.

Generally, hybrid excitation machine (HEM) can be classified into four categories according to the location of PM and FEC. The first type consist both PM and FEC are located at the rotor side [1,2], the second type consist the PM is in the rotor while the FEC is in the stator [3]. The third type the PM is in the rotor while the FEC is in the machine end [4,5]. Others, the last type is both PM and FEC are located in the stator. All HEMs mentioned in the first three consist of a PM in the rotor and can be categorized as "hybrid rotor-PM with FEC machines" while the final machine can be referred as "hybrid stator-PM with FEC machines" [6-9].

Various topologies of HEFSMs have been developed and investigated as shown in Fig.1 [10,11]. Fig. 1(a) illustrates 12S-10P HEFSM which consist of 10 salient rotor pole numbers while the stator core consist of 12 modular C-Type laminated segments placed next to each other with circumferentially magnetized PMs and FEC placed in between them. The arrangement of PMs and FEC is at the same alignment. In addition, this design is build up of 12 DC FEC slots and 12 armature coil (AC) slots. Furthermore, the component part that involved likes PMs, FEC and AC are rectangle in shape thus can make the proposed motor has a very simple structure. This topology has an interest due to their simple and robust rotor design and high torque density. However, the developed C-Type has a problem of separated stator core which lead to difficulty in manufacturing design as well as flux leakage to the outer stator. In order to solve the problem, iron flux bridges have been introduced to the stator core. Because of that, the separated stator core becomes the single piece of core.

The design requirements, restrictions and specifications for the proposed HEFSM are similar for conventional HEV as listed in Table I. The corresponding electrical restrictions to the inverter such as maximum DC bus voltage and maximum inverter current are set to 650V and 360A_{rms}, respectively. Assuming that only a water cooling system is employed as the cooling system of the machine, the limit of the both armature current density, J_a and FEC current density, J_e are restricted to 30A_{rms}/mm^2 and 30A/mm^2, respectively. The outer diameter 269mm and stack length 84mm of main parts of this design machine are identical with conventional motor used in HEV. Commercial FEA package, JMAG-Studio ver.13.0, released by Japanese Research Institute (JRI) is used as 2D-FEA solver in this design.

Various Bridges Topologies

In order to overcome this drawback, several arrangements of iron flux bridges with 0.5mm thickness are designed to the initial C-Type HEFSM as shown in Fig. 2. The main objectives of adding the iron flux bridges to the initial design motor not only can solve the manufacture process

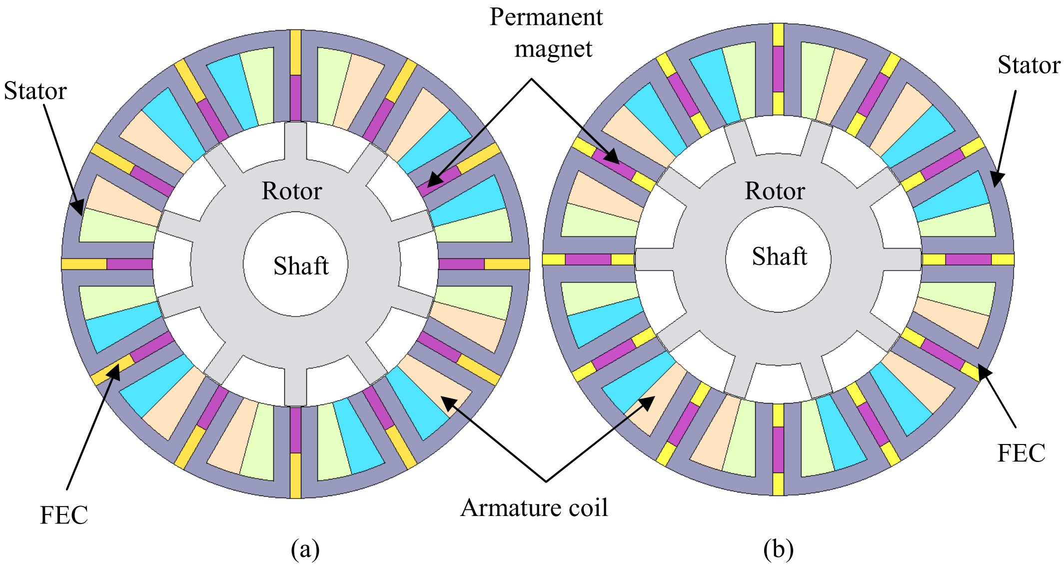

Fig. 1. 12S-10P HEFSM

Table 1. HEFSM motor design specifications and limitations

Items	HEFSM
Maximum DC voltage (V)	650
Maximum current (A_{rms})	360
Maximum J_a (A_{rms}/mm^2)	30
Maximum J_e (A/mm^2)	30
Stator outer diameter (mm)	269
Motor stack length (mm)	84
Diameter of shaft (mm)	30
Air-gap (mm)	0.7
PM volume (kg)	1.3
Max. torque (Nm)	303
Max. power (kW)	123
Width of iron flux bridges (mm)	0.5

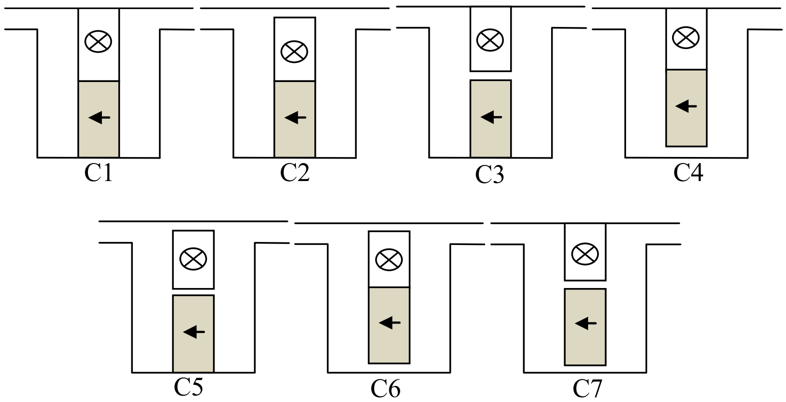

Fig. 2. The arrangement of iron flux bridges

but also can enhance the effectiveness of the FEC with various excitation flux level. Moreover, by increasing the iron flux bridge width in the electrical excitation part, the excitation current utilization will be improved while the excitation loss will be reduced. However, with increasing the thickness of iron flux bridges more PM flux will be short circuited by the iron bridge, which will reduce the utilization ratio of the magnets and machine torque density. The combinations modes of PMs, FEC winding and iron flux bridges will affect the whole performance including reliability (PM demagnetization), PM magnetic short circuit, torque capability and excitation current utilization and excitation loss.

From Fig.1, C1 depicts the initial configuration of C-type HEFSM without iron flux bridge, that inherently affected some flux leakage at the outer stator and inner stator to the air gap. Meanwhile, C2, C3, and C4 illustrate several arrangements with single iron flux bridge attached between FEC slot and upper layer of stator core, between the FEC slot and PM, and between PM and rotor air gap, respectively. It is noticed that, for C2 and C3 conditions, the flux leakage occurs surrounding the PM to air gap, while C4 consists of flux leakage to air and flux disappear surrounding the outer stator, respectively. Furthermore, C5, C6 and C7 represent, iron flux bridges with two possible combinations between PM, FEC slot and stator, correspondingly. However, under this condition, it is noticed that total flux has been reduced due to flux oppose from one bridge to another, which reduced the total performances. Initially, torque performances of all flux bridge combinations are investigated as depicted in Fig. 3. From the graph, it is clear that the highest torque of approximately 189.6Nm is achieved for C2 configuration, while the lowest torque of approximately 174.6Nm is obtained under C4 configuration. This is due to the flux leakage and flux cancellation to the air as well as flux disappears to surrounding upper layer of stator core. As C2 gives the highest torque capability, performances of C2 configuration such as torque and power characteristics with respect to various J_a and J_e conditions are analyzed.

Performance of C2 design

The instantaneous torque characteristics at maximum torque condition in which the FEC current density and armature current density are set to 30A/mm^2 and 30A$_{rms}$/mm^2, respectively are demonstrated in Fig. 4. The average torque reaches 189.6Nm with peak to peak torque of approximately 47.83Nm. Since the peak-peak torque is higher than required minimum value, estimation of flux linkage which contributes to high cogging torque will be investigated and optimized. Moreover, torque versus J_e at various J_a characteristic is represented in Fig. 5. Fig. 5 explains the drive performances of the initial design machine in terms of torque versus FEC current density characteristics of the proposed motor. The graph shows that with increasing in J_e, the torque also increase linearly with the same pattern at 0A$_{rms}$/mm^2 until 20A$_{rms}$/mm^2. In the meantime, similar torque characteristic is obtained at 25A$_{rms}$/mm^2 and30A$_{rms}$/mm^2 in which the torque pattern

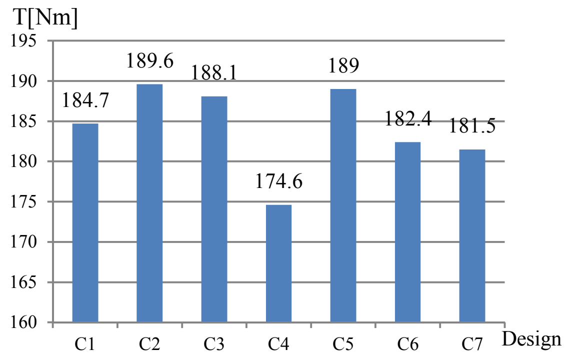

Fig. 3. The maximum torque for all configurations

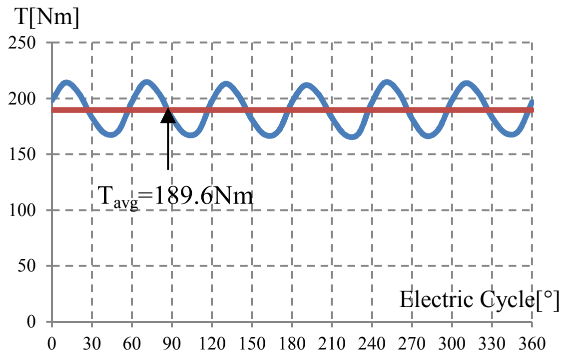

Fig. 4. Instantaneous torque for C2

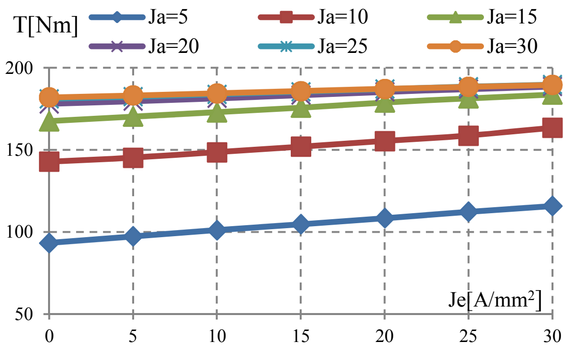

Fig. 5. Torque vs J_e at various J_a for C2

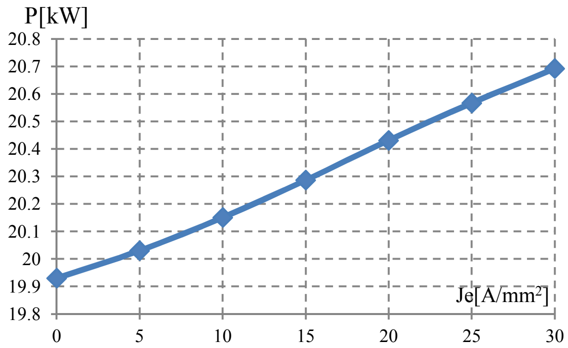

Fig. 6. Power vs various J_e at maximum J_a for C2

is constant. The maximum torque is approximately 189.8Nm when J_a of $25A_{rms}/mm^2$ and J_e of $30A/mm^2$ are set at the base speed 1042 r/min. This is due to low armature coil flux that limits the force to move the rotor.

Finally, the power versus maximum J_a at various J_e is analyzed as depicted in Fig. 6. It is obvious that the power increased linearly with increasing J_e. The maximum power obtained is approximately 20.7kW at maximum J_a and J_e.

Conclusion

In this paper, several topologies of the iron flux bridge for C-Type 12S-10P HEFSM have been overviewed and discussed. The main objectives of adding the iron flux bridges to the initial design motor not only can solve the manufacture process but also can enhance the effectiveness of the FEC with various excitation flux level. It can be conclude that configuration 2 with single iron flux bridges located at outer FEC produces higher torque and power with approximately 189.6Nm and 20.7kW, respectively when compared with the other design. Lastly, the performance of torque and power have been analyzed and compared.

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