Analysis of Double-Stator Switched Flux PM Machines with Non-overlapping Concentrated Windings

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Abstract. Permanent magnet (PM) synchronous machines having double-stator and equipped with non-overlapping concentrated windings, is analyzed in this paper. Thus, there is reduced copper loss, resulting to improved efficiency. Basically, the analyzed machine is a doubly-salient stator-PM machine, with a rotor made of modulating steel ring. The analysis includes the open circuit and on-load characteristics of the developed machines. Furthermore, a quantitative comparison of the electromagnetic analysis of the machines having different winding topology is also detailed in this study. The investigation shows that the even-rotor pole machines are characterized by higher cogging torque as well larger torque ripple, relative to their odd-rotor pole counterparts, due to their high possession of harmonics.

Keywords: Cogging torque, concentrated windings, double-stator, torque ripple, total harmonic distortion.

1 Introduction

Research has shown that permanent magnet machines especially the interior permanent magnet (IPM) type, are capable of operating over a wide speed range. Hence, it has good flux-weakening potential [1]. Numerous advantages of permanent magnet (PM) machines have led to its widespread investigation. Thus, more efficient PM machines with different designs are still emerging. More so, PM machines could deliver higher output torque and power than their equivalent machines that are free of PMs. Permanent magnet synchronous machines are associated with improved efficiency, high reliability and good fault-tolerant capability [2] and [3]. Nevertheless, the scarcity and soaring prize of magnet materials has led to intensive research on magnet less machines as seen in [4]. Double-stator switched flux permanent magnet (DS-SFPM) machine utilizing ferrite magnets is analyzed in [5]. The recent growing research interest in the area of design and analysis of PM machines could also be attributed to the emergence of high energy density rare-earth magnets as well as the recent advances in power electronics, design and control of PM machines.

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In most PM machines, the permanent magnets are located in the rotating part of the machine. However, as shown in this study, PMs can also be housed in the stationary part of electric machines. Thus, based on the location of permanent magnets on the rotor or stator of the machine, PM machines could be classified as either rotor- or stator-PM machines, respectively. The rotor-PM machines have been researched extensively due to their high output torque and power capability. However, it has been shown that the rotor-PM machines are characterized by poor thermal management compared to their stator-PM counterparts [6]. Therefore, the rotor-PM machines have higher demagnetization potential compared to their stator-PM counterparts [7]. The common types of stator-PM machines are the doubly-salient [8], flux reversal [9] and switched flux [10] PM machines. Some of the attractive features of flux reversal PM machines include: simple and rugged rotor structure which is good for high speed operation and their low inductance, desirable for fault-tolerant applications [9], [11] and [12]. However, one of the major disadvantages of the flux reversal PM machines is their high risk of demagnetization [13], owing to the series combination effect of the magnetic flux of both the armature windings and the permanent magnets. They also have high leakage flux [14] compared to other PM machines. In addition, flux reversal PM machines have high cogging torque/torque ripple characteristics [15]. The switched flux PM machines, generally have more sinusoidal back-electromotive force (EMF) waveforms and consequently less harmonics and ripples than the above two mentioned stator-PM machines. In this investigation, a precise account of cogging torque, torque ripple, total harmonic distortion and the overall torque performance of the analyzed double-stator PM machines is given on different load conditions.

2 The Machine Structure

The mechanical structure of the DS-SFPM machine is similar to that of a double-stator switched reluctance machine given in [16], although with some differences. Essentially, the developed machine consists of doubly-salient stators and a sandwiched cup-rotor which serves as a flux-modulator. Figure 1 shows the structure of the machine under study.

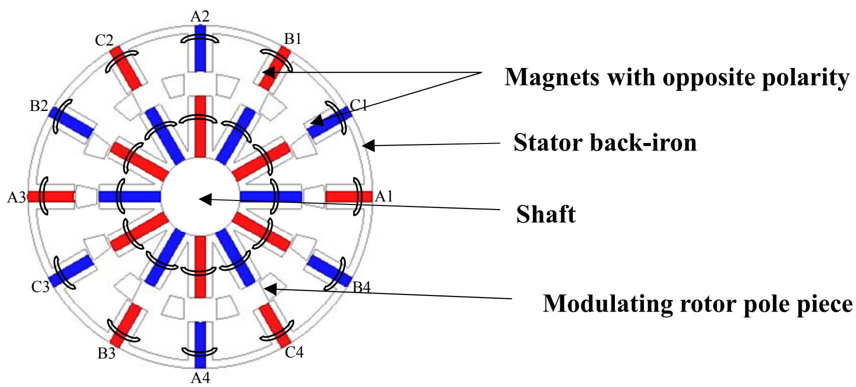

Fig. 1. Cross-section of the analyzed machine.

Note that field excitation of the developed machines is mainly due to the permanent magnet. The polarity and magnitude of the flux-linkages change with respect to the rotation of the modulating ring. This periodic change of flux-linkage with the rotating modulating iron segments will induce an EMF in the machine and consequently torque production. The spoke-mounted PMs in this paper are capable of concentrating the generated magnetic flux around the air-gap for improved torque production.

All the analyzed machines are optimized using the evolutionary optimization technique with the goal to achieve maximum average torque. In a bid to maintain the same level of copper losses in the inner and outer stators, the number of turns per coil in both stators is allocated in proportion to the ratio of its slot areas. The machine size including the active length and the outer diameter as well as the total number of turns per phase is kept the same in the comparison in the whole analysis for fairness. It is worth mentioning that, we adopted the non-overlapping concentrated winding style, in order to reduce the copper loss in the coils. Thus, enhancing the overall efficiency of the analyzed machines.

The rotor electrical and mechanical degrees of the developed machines are related by:

$$\text{Elect\_deg.}=N_r \text{Mech\_deg.} \tag{1}$$

where N_r is the rotor pole number.

Similarly, the stator and rotor pole combinations (Ns and Nr) of the analyzed machines are given by:

$$Nr=Ns\pm j \tag{2}$$

where j is an integer 1 and/or 2. The feasible stator and rotor pole combinations of the analyzed machines are similar to those stated in [17]. In this study, ALL-W and ALT-

W denotes all-pole wound and alternate-pole wound topology, respectively. Note that, the main parameters of the analyzed machine are listed in Table 1.

Table 1 The analyzed machine parameters

Parameter	Value
Outer stator slot number	12
Inner stator slot number	12
Air-gap length (mm)	0.5
Active axial length (mm)	25
Stator outer diameter (mm)	90
Number of phases	3
Total number of turns/phase	72
PM remanence (Tesla)	1.2
Split ratio	0.66
PM relative permeability	1.05

3 Open Circuit Waveforms

Fig. 2 shows the cogging torque waveforms and spectra of the analyzed machines under open-circuit condition. The cogging torque of the analyzed machines having even-rotor poles is quite large especially that of the 10-pole machine when compared with the analyzed odd-rotor pole machines. This is likely due to the existence of the 5th and 7th harmonic order of the back-EMF. It is worth noting that, the cogging torque orders of the analyzed machines having even- and odd-rotor pole numbers are multiples of six and twelve, respectively. The high cogging torque seen in the even rotor machines could be minimized by considering this factor in a multi-objective design/optimization process, but usually at the expense of some percentage of the electromagnetic torque.

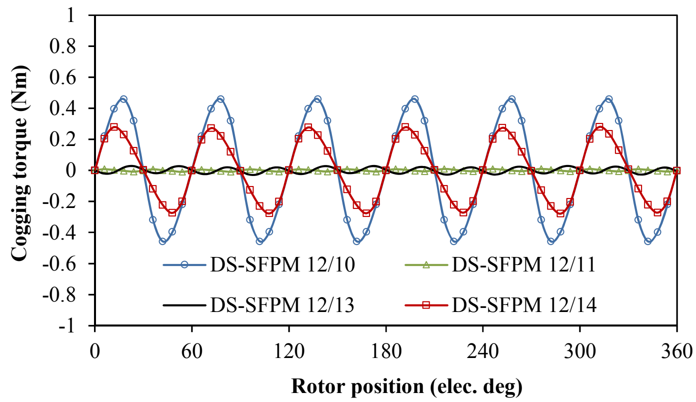

Figure 2(a) Waveforms

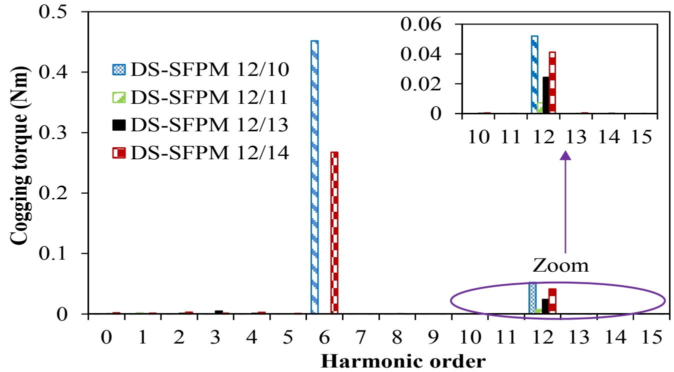

Figure 2(b). Comparison of cogging torque in the analyzed machine.

Meanwhile, in order to predict the voltage harmonics of the machines, the total harmonic distortions (THD) in the back-EMFs is evaluated in equation (3);

$$THD = \frac{\sqrt{\sum_{i=2}^{\infty} V_i^2}}{V_1} \quad (1)$$

where V_i is the *rms* value of the *ith* harmonic, and V_1 is the fundamental magnitude of the back-EMF. The variation of the THD under different load conditions is shown in Fig. 3. It is obvious, that the total harmonic distortion of the voltage increase with input current. Note also, that the analyzed 14-pole machine having all-pole wound configuration has the least variation of THD with varying load due to its more sinusoidal EMF features.

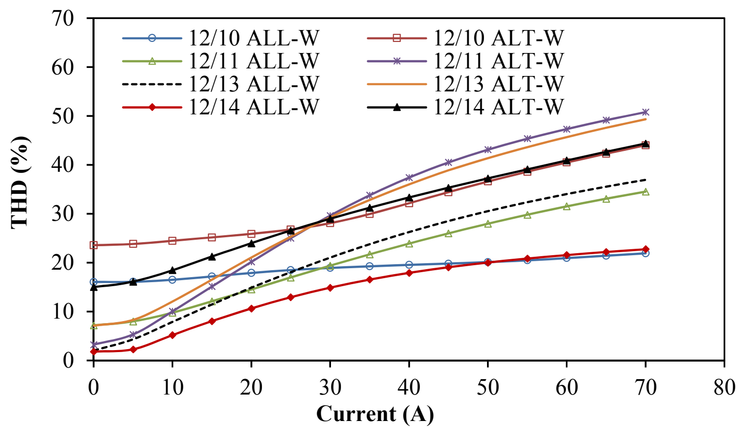

Fig. 3. Variation of total harmonic distortion with current.

The comparison of torque ripple at different peak currents is depicted in Fig. 4. Obviously, the developed machines having Nr=even exhibits higher torque ripple than their odd-rotor pole counterparts. This is because the machines with even-rotor pole numbers are characterized by a large amount of harmonics.

The torque ripple which is the ratio of the difference between the maximum and minimum torque to the average torque over one electric cycle is given by:

$$T_{\text{ripple}} = \frac{(T_{\max} - T_{\min})}{T_{avg}}(100) \quad (4)$$

where Tmax, Tmin, and Tavg are the maximum, minimum and average torque, respectively. Fig. 4. Shows the variation of torque ripple with current.

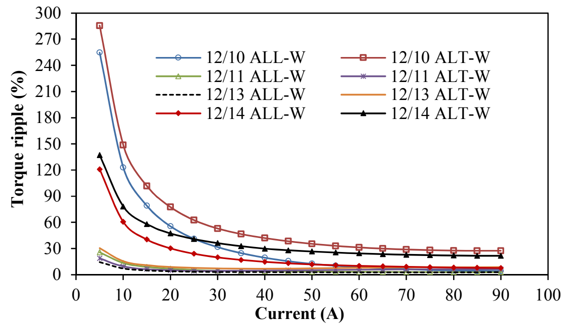

Fig. 4. Variation of torque ripple with current.

The variation of electromagnetic torque over the rotor positions with their corresponding spectra is given in Fig. 5. It is worth noting that, the 12-slot/14-pole machine having all-pole wound topology exhibits the largest torque density and highest peak-peak output torque amongst the compared machines.

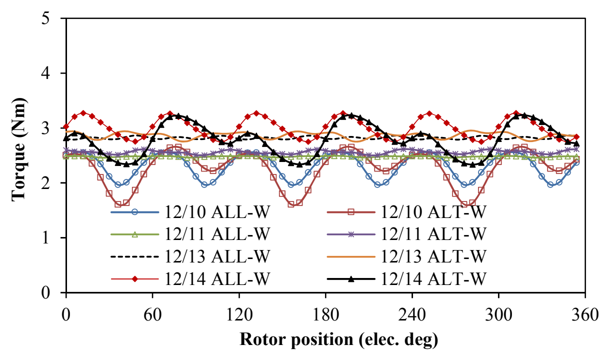

Fig. 5(a) Waveforms

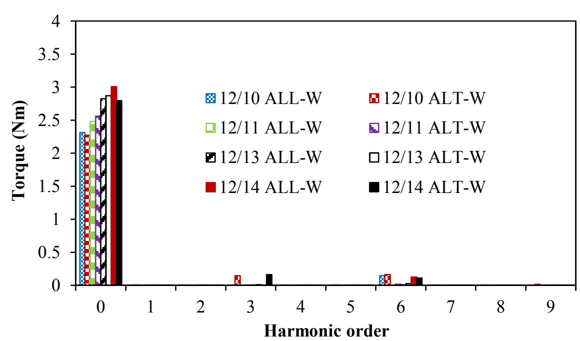

Fig. 5(b) Variation of torque with rotor position when copper loss = 30W, i_d=0.

Figs. 6 and 7 show the variation of current and copper loss with the average torque, respectively. It is worth mentioning that, the analyzed 14-pole machine has the best overload withstand capability amongst its counterparts.

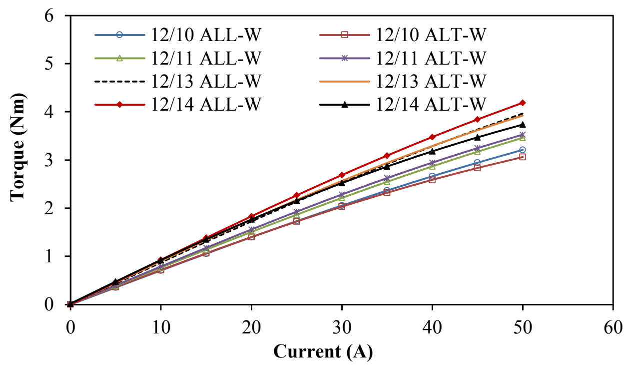

Fig. 6. Variation of torque versus current when i_d=0.

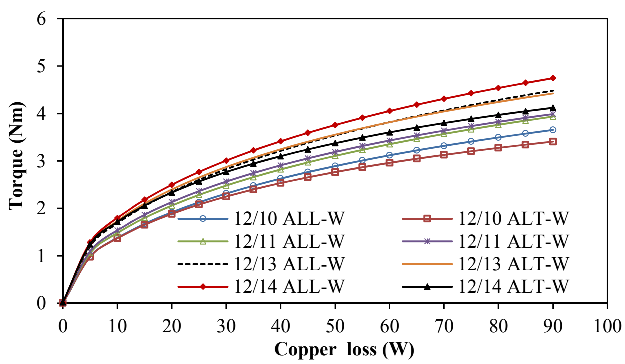

Fig. 7. Variation of torque versus copper loss, i_d=0.

5 Conclusions

The performance analysis of double-stator SFPM machines having non-overlapping concentrated windings is detailed in this paper. Thus, there is reduced copper loss, resulting to improved overall performance. The analysis shows that the even-rotor pole machines are characterized by high cogging torque and torque ripple. This is an undesirable effect which could lead to acoustic noise and vibration in a given electrical machine. Furthermore, it is seen that the total harmonic distortion of the voltage is essentially directly proportional to the applied load. Moreover, the analyzed

12-slot/14-pole machine exhibits the largest torque profile amongst all the compared machines.

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