Investigation of influence the slot/pole combinations on the torque performance for synchronous reluctance machine with distributed and concentrated windings

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Abstract. This paper explores the electromagnetic performance comparison of three different types of synchronous reluctance machines. The investigated machines including, conventional full pitch distributed winding (24 slots /4 poles), an integer slot concentrated nonoverlapping winding (12 slots /4 poles), and fractional slot concentrated nonoverlapping winding (15 slots /8 poles). A finite element analysis JMAG Designer is used to validate the performance for all machines, and have been employed for the optimisation process to improve the torque density as well as to minimise torque ripple. Meanwhile, the current density, slot filling factor and specific dimensions, viz., stator outer diameter, stack length and air gap are designed to be constant. The result shows that for a DW-SynRM, a high value of average torque is achieved, and the torque ripple is lower. The result also demonstrates that the FSCW-SynRM can reach a low torque oscillation. Meanwhile, the ISCW-SynRM exhibit a high reluctance torque, but the torque ripple is a big challenge. On the whole, the distributed winding machine has the best performance compared to concentrated winding machines.

1. Introduction
Permanent magnets (PMs) machines exhibit some features, including high torque/power density and high efficiency over induction and switched reluctance machines [1]. However, there are disadvantages such as scarcity of resources and high cost of magnetic materials [2]. At the same time, in recent years, the impact of global warming has led to the decreasing trend of global fossil fuel consumption. The reasons above may contribute to encourage the researchers to develop and manufacture new machines with less or even without PMs to the surface as alternative solutions [3].

Concerning the drawbacks of permanent magnets (PMs) machines, Synchronous reluctance machines (SynRMs) come into consideration and have been received a more interest for various features and reasons. The obvious advantages of these machines are simplicity of the machine construction and their ruggedness of the rotor structure, because an absence of permeant magnets, SynRM will be an excellent choice to reduce manufacturing cost [4]. Furthermore, high efficiency and low rotor temperature are given mainly because of the absence of the rotor windings. Hence there are no rotor
copper losses over induction motors [5]. Another advantage offered is the high-power per volume ratio, which is favourable to use in high-speed and harsh environment applications [6–8].

The SynRM s were introduced by Kostko [9]. It is working on the principle of reluctance torque, which generates electromagnetic torque only by the difference between quadratic and direct-axis inductances (Lq) and (Ld), respectively [10]. In order for SynRM to have acceptable performance, the rotor is required to be designed to achieve a high anisotropy ratio, which has a maximum reluctance in the q-axis and minimum reluctance in the d-axis [11].

Similar to induction machines, SynRMs are traditionally using the stator with distributed windings (DW) as shown widely explored topic in literature. Consequently, sinusoidal magnetomotive force (MMF) in a SynRM is typically obtained by DW, higher torque density and lower torque ripple also can be achieved when utilising DW. On the other side, concentrated winding machines (CW) have become attractive, more investigations a few years before. In [12,13], the authors presented a new concept where the fractional slot concentrated windings (FSCW) have been applied to SynRMs. The results show that the SynRM with FSCW making the machine easier to construct and more robustness, increased slot fill factor, added thermal improvements, thereby the efficiency distinctly increased.

The design and improvement of the SynRM performance have been a subject of many studies in the bibliography [14–19]. Nevertheless, the authors focused on the influence of the rotor geometry on the output torque. Research on the effect of layers on SynRMs has not been extensively discussed in the literature, only [5] considered it, but did not study it in depth. Among them, they have investigated the stator slot/pole number combinations for a single layer of flux barrier, and the influence of the number of the flux-barrier layers have been studied just for a machine with 24 slots /4 poles. In [20], the authors have compared the 36 stator /4 poles and 12 stator /4 poles machine without considering the influence of the number of the flux-barrier layers on the machine performance.

The key purpose of this paper is using 2D finite element analysis (FEM) to study the influence of stator slot/pole number combinations together with the layer number in synchronous reluctance machines. The proposed machines DW-SynRM (24 stator /4 poles), FSCW-SynRM (15 stator /8 poles), ISCW-SynRM (12 stator /4 poles) are optimised against the same current and current density. The paper is organised as follows: firstly in section 2, the machine specifications are explained, besides optimisation design of multi-layer flux barrier for 24/4 DW-SynRM and 12/4 CW-SynRM are analysed with consideration of barrier shape parameters, viz. width, length and position; in section 3, the investigated machines performance is comprehensively compared in terms of flux density in the air gap, magnetic field distribution through stator and rotor and the torque behaviours. Finally, section 4 presents the main conclusions and findings of this study.

2. Design Optimisation of SynRMs
A comprehensive comparative study of the three models of SynRMs was done. To perform a fair comparison throughout this study, the main machine geometric parameters as, stator outer diameter, the stack length and air gap length are selected to be constant for each machine. The current and current density are also the same. The corresponding candidate machines with different windings and rotor topologies have been designed and evaluated by FEM software (JMAG Designer).

2.1. Machine Specifications
The cross-sections of DW-SynRM (24 stator /4 poles), CW-SynRM (15 slot /8 poles, 12 slot /4 poles), are shown in figure 1, and the machine specifications and geometry parameters are listed in table 1.
Figure 1. Cross-sections of SynRM machines. (a) DW-SynRM. (b) FSCW-SynRM. (c) ISCW-
SynRM.

Table 1. Main Parameters of The Compared Machines [20].

|                          | Distributed Winding | Concentrated Winding |
|--------------------------|----------------------|----------------------|
|                          | 24 Slot / 4 Pole     | 15 Slot / 8 Pole     |
|                          | 12 Slot / 4 Pole     |                      |
| Stator Outer Diameter (mm) | 270                  | 150                  |
| Rotor Outer Diameter (mm) | 150                  |                      |
| Shaft Diameter (mm)       | 60                   |                      |
| Stack Length (mm)         | 140                  |                      |
| Air Gap Thickness (mm)    | 0.4                  |                      |
| Rated Current (A)         | 275                  |                      |
| Rated Speed (rpm)         | 5730                 |                      |
| Steel Grade Stator & Rotor| M235-35 A            |                      |
| Stator Tooth width (mm)   | 11                   | 22.8                 |
| Stator Yoke height (mm)   | 34                   | 26                   |
| Stator Slot height (mm)   | 25.6                 | 33.6                 |
| Slot Opening (mm)         | 2.8                  | 3.4                  |
| Number of Turns per phase | 20                   | 30                   |
| Number of Winding Layers  | 1                    | 2                    |

2.2. Influence of Flux-Barrier Layers

This part will study the impact number of rotors composed of one, two, three and four flux barriers per pole on its electromagnetic performance; this approach has been presented in [5,15]. Study the sensitivity of different rotor barriers per pole on output torque; only two machines have been considered. It is thought that by using one of DW-SynRM and CW-SynRM, it is enough to present the impact of layer numbers on the machine performances, thus simplifying the analysis process. The 24 slot/4 pole and 12 slot /4 poles were optimised by FEM to achieve the maximum average torque when both machines having the same stator in the previous part is adopted for cost-effective.

Figure 2 shows the torque behaviour for 24 slot/4 poles machine with a various number of flux barrier layers. It can clearly be seen that the three and four number of the rotor flux barrier layers practically have the same value of average torque. However, the average torque of the rotor machine with three flux barrier per pole is slightly higher than another machine with four-layers, which are (132.59 and 132.28 N.m) respectively. At the same time, the rotor with a single layer of flux barrier has the lowest torque density. The best torque ripple achieved by configuration of a rotor with three flux barriers, and double flux barrier has a higher value of the torque ripple compared to other machines.
Figure 2. Comparison of average torque and torque ripple for (24 slot/4 poles) SynRM with different flux-barrier layer number.

The second design is 12 slot/4 poles SynRM machine is given in figure 3, which reports the torque and torque ripple of the four-rotor configurations presented previously. It obviously shows that both torque and torque ripple are affected at the same time by changing the rotor layers. From figure 3 it is evident that the increase of flux barrier numbers yielding a noticeable rise of average torque for all machines, where can be understood from this context that the four layers of flux barrier have the highest torque. In contrast, this configuration exhibits the highest torque ripple when a single flux barrier is implemented. Besides, the rotor machine of the three layers has the lowest value of torque ripple.

Figure 3. Comparison of average torque and torque ripple for (12 slot/4 poles) SynRM with different flux-barrier layer number.

3. Machine Comparison

This section will compare the final results of the three designed machines after optimised the geometrical dimensions of the rotor. Meanwhile, the stator geometrical dimensions are designed to be identical. A comprehensive evaluation on the performance of proposed machines with different windings and rotor topologies can be made in terms of flux density in the air gap, magnetic field distribution through stator and rotor and the torque behaviours.

3.1. Magnetic Flux Density and Flux Density Distributions

The calculated flux density and filed distributions obtained by FEM for the three machines when the current is 275A are presented in the figure. 4. It can be clearly seen that the machine structures have been magnetised appropriately and it is demonstrated highly saturated in the rotor flux barrier ribs.

The flux density waveforms with a current of 275A are compared in figure 5. As clearly shown, the slotting impact on the air gap flux density, which is the distributed windings (24/4 DW-SynRM) shows some more sinusoidal distribution of the flux density while concentrated winding machines (15 slot /8 poles, 12 slot /4 poles) have a much poorer sinusoidal wave-shapes compared to DW-SynRM.
3.2. Torque Comparison

The reluctance torque curves of the investigated machines are compared at rated conditions, where the current is 275A and its nominal speed of 5730 rpm when the end-windings are deserted.

The torque waveforms after optimisation for DW-SynRM (24 stator /4 poles), CW-SynRM (15 slot /8 poles, 12 slot /4 poles) are compared in figure 6. As represented in figure 6(b), The average torque of the three machines is 136.17 Nm, 107.75 Nm and 110.24 Nm, and the torque ripple is 21.5%, 15.24% and 35.3% respectively. It is noted that the 24 slot/4 pole generates the highest reluctance torque. Thanks to the high number of poles in the rotor and a high number of slots in the stator as well, machine with 15 slot /8 poles, good quality of torque ripple is reported when considering this design. In addition, the 12 slots /4 pole topology, achieve barely higher output torque than 15 slot /8 poles topology. And as expected, exhibits the highest level of torque ripple compared to these latter referred to the low number of stator slots. Therefore, 12 slots /4 pole machine will be employed for further investigation of end windings effects on the motor performance.
4. Conclusion
This paper has dealt with the design, analysis and comparison of the electromagnetic performance for three different machines of SynRMs. Firstly, the influence of the rotor flux-barrier numbers on the torque performance is discussed. The results show that the 24 slot/4 poles with three and four flux barriers have almost the same torque. However, the three flux-barriers have a lowermost torque ripple. It was shown that increasing the flux barrier numbers leads to a noticeable rise of average torque for the 12 slot/4 pole machine. In addition, the best torque ripple remains in three flux barriers. The DW machine exhibits more sinusoidally flux density waveforms over CW machines.

The influence of slot/pole combinations has been investigated; the DW machine generates the highest reluctance torque than the ISCW and FSCW-SynRM. However, the more poles of the FSCW motor, the smaller the torque fluctuation. While ISCW-SynRM has a poorer torque ripple which is known as a main Inherent drawback of this topology. Therefore, the future work will be to develop this topology with considering of the end winding influence.

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