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Influence of Winding Configuration on the Performance of Surface-Mounted PM Machines

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***Abstract*—This paper presents a detailed performance comparison of Surface-Mounted PM machines (SMPMMs) equipped with distributed and concentrated windings. In order to reveal the merits and demerits of these kind of winding configurations three SMPMMs have been designed with identical air-gap length, stator and rotor outer and inner dimensions, number of poles and stack length. This comparative investigation is performed by using finite element analysis. Key parameters and performance characteristics, such as leakage-inductance, back EMF, average torque, torque quality, machine losses, and efficiency are compared.**

***Index Terms*—electric machines, surface-mounted PM machines, distributed winding, concentrated winding, MMF harmonics, winding factor**

I. INTRODUCTION

The application of SMPMMs is extending due to high power density and wide operating speed range with the help of reluctance torque and field weakening control. In the recent years, the application of surface permanent magnet motors is expanding because of their advantages for energy conservation, clean energy, etc. They are used in some electric cars, Railway Vehicles, and electric power steering and in a variety of industrial motors. In order to maximize the advantage of its high power density, distributed winding can be one of the reasonable choices for winding designs, Comparing to distributed windings, concentrated windings enables easy winding automation and have short end windings, smaller copper loss, and require smaller space than distributed windings [1]-[3].

To improve output torque of PM machines with concentrated windings, many researches dealing with improving output torque of PM machines are undergoing. In design aspects, to improve the output torque, unequal tooth width of stator and appropriate choice of slot and pole number are introduced and the researches achieved improvement of output power of PM machines with concentrated windings or gives the direction in initial design stage [2]-[4]. However, the researchers are concerned only with SPM motor with concentrated windings. Unlike to the SPM motors, inductances vary with rotor position and current phase angle in IPMSM, and this variation have significant effects on motor performances. There is a substantial amount of work that has been published on PM synchronous machines (both surface and interior PM) with Integral-Slot Distributed Windings (ISDW) [2], [5]-[7] as well as FSCW surface PM machines [8]-[14]. In contrast, the design, analysis, and comparison of difference winding topology in PM machines have received relatively limited attention in the literature to date [15]-[17].

The purpose of this paper is to study the effects on the characteristics of PMSM when 10-pole machines with 9, 15, and 30-slots have been designed. SPMSM with distributed windings is designed, and then with concentrated windings is designed with identical rotor part of SM. From basic parameter to output characteristics, concentrated and distributed windings has been closely compared. From the basic motor parameters and characteristics, such as Back-EMF waveforms and their harmonic spectrums, output torque, machine losses, and efficiency, are compared and design strategy about winding configuration is discussed.

II. INFLUENCE OF WINDING CONFIGURATION

As known well, the operating principle and modes of an electrical machine is based on the interaction between the magnetic fields and the currents flowing in the stator windings of the machine. Stator winding produces the rotating-field that produces the torque. The waveform of this rotating field, determined by the winding configurations, is very important in terms of parasitic effects such as torque ripple, noise and vibration, and performance characteristics such as current-voltage harmonics, machine losses, etc.

To be able to reveal the influence of the winding configuration on the performance of a SMPMM, 10-pole machines with 9, 15, and 30-slots (9Q, 15Q, and 30Q) have been designed. For one-turn and one-ampere, the obtained MMF waveforms of these machines are illustrated in Fig. 1. 9Q and 15Q fractional-slot concentrated winding (FSCW) machines while the 30Q is a conventional machine with three slot-pitch distributed windings.

Especially the 9Q machine has the most distortion on its MMF waveform. While 30Q and 15Q machines have only the super harmonics, the 9Q machine has also sub-harmonics. Therefore, it can be concluded that, in terms of MMF and winding factor harmonics, the machines which belong to stator slot/phase/pole number (q) is equal to 0.5 and $q = 1$ families, show similar characteristics [18].

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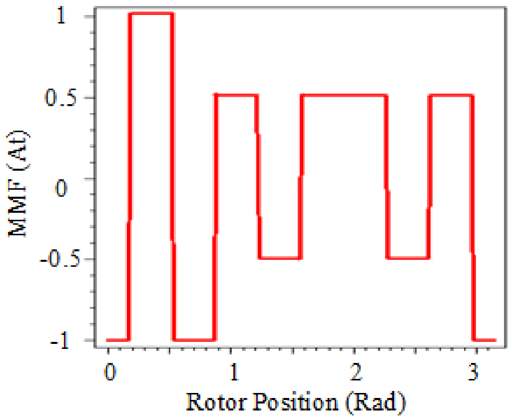
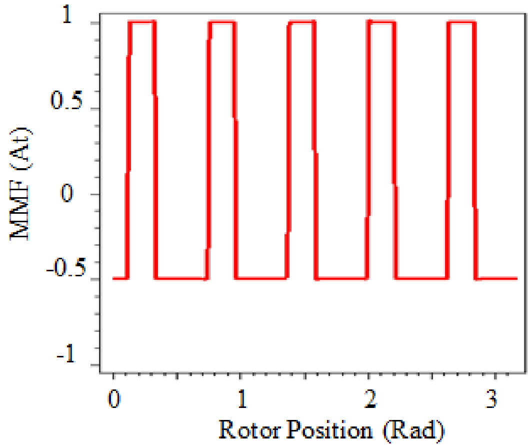
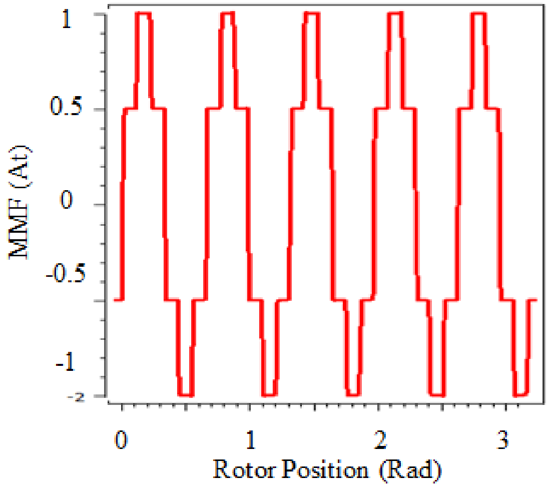


(a) 9Q



(b) 15Q



(c) 30Q

Figure 1. 9Q10P, 15Q10P, and 30Q10P SMPMMs' MMF waveforms for 1 turn and 1 amp

III. ANALYSIS MODEL

The SMPMMs are designed by using the specifications given in Table I. As seen in the table expect for stator slot number and turn number per coil, all other specifications are identical. In order to drive the machines, a Y-Type 3-phase circuit has been used. When the transistors are fed with the rated voltage given in Table I, the developed stator-winding phase "A" current for each machine is shown in Fig. 2. Since the winding factor of the designed machines are different, each machine require different number of turns per coil. In order to determine the number of turns per coil, by keeping the coil cross-sectional area at a specific mm^2, a parametric analysis has been performed and the obtained result is illustrated in Fig. 3. The number of turn, which gives the maximum torque, has been assigned to machines in order to make a fair comparison.

TABLE I. SPECIFICATIONS

Specification	Value
Stator outer diameter (mm)	120
Stator inner diameter (mm)	75
Air-gap length (mm)	1
Shaft diameter (mm)	26
Stack length (mm)	65
Rated power (kW)	3
Rated speed (rpm)	1500
Rated voltage (V)	220
Rated frequency (Hz)	125
Number of poles	10
PM material	NdFeB35
Iron Core material	M19_24G

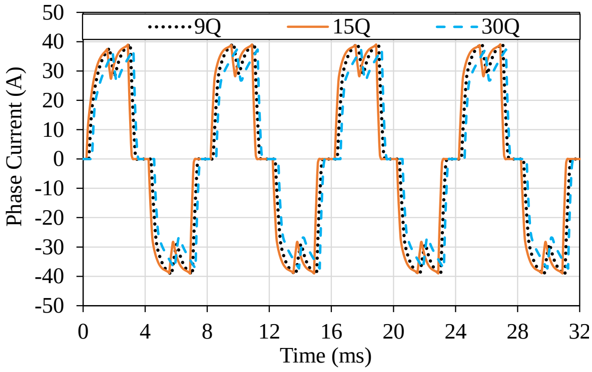


Figure 2. Stator winding phase "A" current waveform.

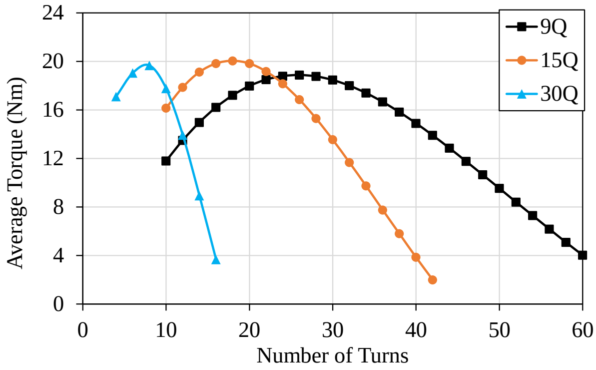


Figure 3. Average torque versus number of turns curves of the 9Q, 15Q and 30Q SMPMMs.

IV. PERFORMANCE EVALUATION

To be able to investigate influence of the MMF harmonics due to the winding layout, ten-pole SMPMMs with 9, 15, and 30-slots have been designed and analysed by using FEA based packed-program ANSYS-Maxwell. All machines are simulated under the same operation conditions (Table I).Obtained results are compared to each other and presented as follows. Back-EMF waveforms and their harmonic spectrums are illustrated in Fig. 4 and Fig.

5. As expected, the levels of 9Q10P machine’s harmonics are the highest while the 30Q10P machine’s is the lowest.

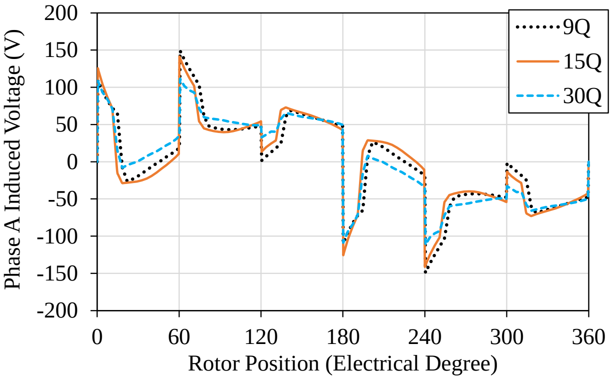


Figure 4. Back-EMF waveforms.

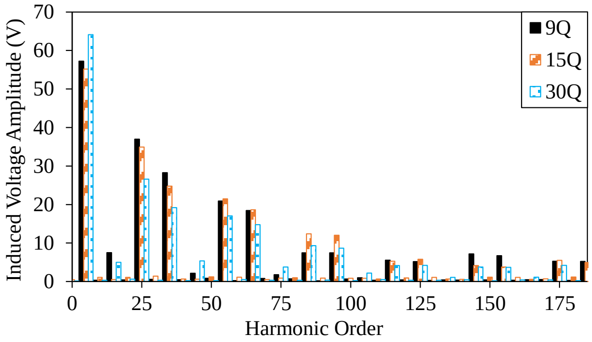


Figure 5. Back-EMF harmonic spectrums.

Torque variation with respect to time is illustrated in Fig. 6. As seen in the figure, designed machines have very high torque ripple rates, especially; FSCW SMPMMs. The average toque values are very close to each other.

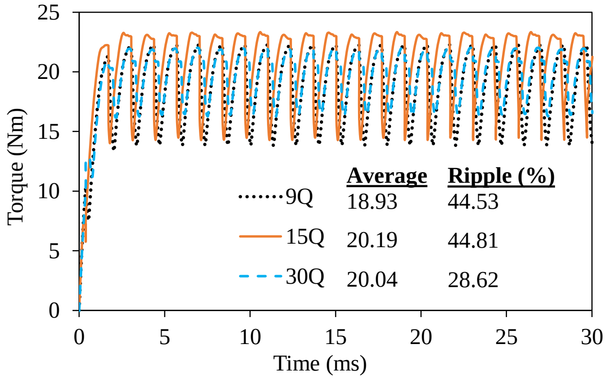
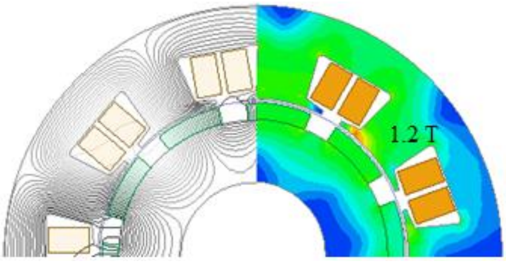
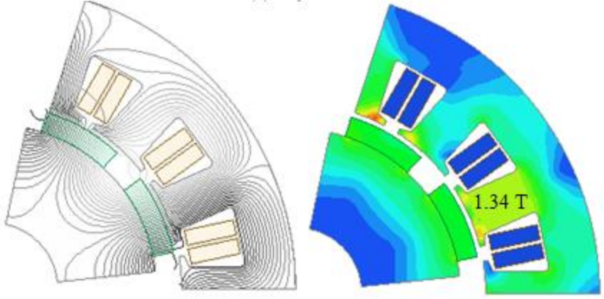


Figure 6. Torque variation with respect to time.

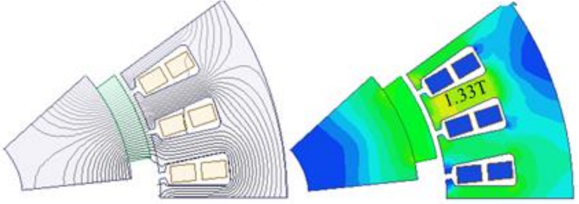
Flux line and flux density distributions of the machines are illustrated in Fig. 7. It is clear from the flux density distributions figures that the rotor yoke thickness of the machines can be reduced more. On the other hand, it is also visible that the stator yoke thickness of 15Q10P machine can be reduced more in order to reduce the total weight and active material consumption. Therefore, it is clear that designed machines require optimization. In this study, only the initial designs have been considered. Furthermore, it is clear that, there are some local saturated parts, especially; stator tooth tips are saturated highly.



(a) 9Q10P



(b) 15Q10P



(c) 30Q10P

Figure 7. Flux line and flux density distributions of the designed machines.

TABLE I. PERFORMANCE CHARACTERISTICS

Parameter	**9Q**	**15Q**	**30Q**
Leakage Ind (mH)	0.97	0.55	0.58
Total Weight (kg)	4.755	4.605	4.68
P_{cu} (W)	263	297.2	369.22
P_{PM} (W)	0.045	0.009	0.0022
P_{core} (W)	26.21	28.48	31.27
P_{other} (W)	29.74	31.72	31.48
P_{out} (W)	2974	3172	3148.1
Efficiency (%)	90.31	89.87	87.93

Comparison of performance characteristics has been given in Table II. The higher leakage inductance is a typical property of FSCW machines. This is due to the weak contact between the coils of the phases. On the other hand, the machines designed by using distributed windings can also have a higher leakage inductance if the teeth are designed very close to each other. Because of this reason, the leakage inductances of 15Q and 30Q machines are similar. As expected, the stator copper loss P_{cu} of 30Q machine is the highest because of its long end-windings. However, 30Q machine has the minimum PM loss due to its lower MMF harmonics. As seen in the table, total weights are almost the same since the same materials and the same specifications have been used. It is also clear that, even if the output power of the 9Q machine is the lowest, its efficiency percentage is the highest. Therefore, it has been revealed that, a more compact and higher efficiency SMPMMs can be designed by using different slot/pole combinations that follows the $q < 0.5$ rules. However, for large SMPMMs PM loss should be considered carefully. It can be concluded that in terms of weight and core loss, there is no difference between concentrated and distributed windings. However, there is a significant difference in terms of PM and copper losses.

V. CONCLUSION

In this paper, the merits and demerits of concentrated and distributed windings has been compared by implementing concentrated windings to 9Q10P, 15Q10P and distributed winding to 30Q10P SMPMMs. The main merits of using concentrated winding is that it cause higher torque ripple, cogging torque and hence noise and vibration. In addition, since their MMF harmonics are significantly high, their eddy current loss of PM is higher. However, the SMPMMs designed with the concentrated windings have relatively higher efficiency since their end-windings are quite shorter. On the other hand, even if the efficiency of the SMPMM designed by using the distributed winding is lower than those which designed by using concentrated windings, it shows a good performance in terms of torque ripple, cogging torque, noise, vibration, and PM loss. Since the limited space, power density and the efficiency are very important parameters in terms of electrical vehicle and aerospace applications, the FSCW technique should be improved. In order to increase the usefulness of the FSCW technique, some investigations such as multi-phase FSCW configurations and their combination with flux barriers will be conducted in the future works.

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