

EVS29 Symposium

Montréal, Québec, Canada, June 19-22, 2016

Comparative Study of Permanent Magnet Machines with Similar Slot and Pole Numbers For Electric Vehicle Application

Aimeng Wang, Lijuan Chang, Shuhui Dong

*State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources,
North China Electric Power University, 619 North of Yonghua Street, Baoding, Hebei, China
E-mail: aimeng_068@163.com*

Abstract

This paper presents a comparative study of four types of surface mounted permanent-magnet (PM) machines with similar slot and pole numbers and different winding configurations for electric vehicles, that is, 12 slot/10 pole and 12 slot/14 pole machines with either all the teeth or alternative teeth carrying a concentrated non-overlapping coil. Finite element (FE) model of the machines are developed to analyze their performance. Results show that 12 slot/14 pole machine which pole number is higher than slot number has higher electromagnetic torque, lower cogging torque and torque ripple than 12 slot/10 pole machine. The total harmonic distortion (THD) of machine is lower when all the teeth are wound while the fault tolerance of machine with alternative teeth wound is better.

Keywords: electric vehicle (EV); motor; torque; finite element calculation; simulation

1 Introduction

Environmental pollution and gradual depletion of petroleum resources brings serious challenges to motor vehicles, people are paying more and more attention to the development of new energy-efficient vehicles such as electric vehicles [1].

PM machines are widely used in traction application of electric vehicles because of their performance advantages including wide constant-power speed range, high power density and high efficiency [2]. For conventional motors, the typical ratio of slot number and pole number is 3/2. In order to improve the power density and torque density of

permanent magnet machine in a maximum extent, similar slot and pole numbers combinations and non-overlapping concentrated stator windings are often employed. The concentrated winding machines have the advantages of shorter end windings, lower copper losses and hence lower manufacturing cost. And when the concentrated winding are used, the coils can be wound either on all the teeth or alternative teeth. And for the latter one, the phase windings are isolated from each other hence they have higher fault tolerance, which is desirable for electric vehicle application.

The 12 slot/10 pole and 12 slot/14 pole 230W PM machines are chosen to investigate and discuss their

advantages and disadvantages for electric vehicles application in this paper. Machines in which either all the teeth or only alternative teeth carry a coil are considered, and ordinary fractional slot 15 slot/10 pole machine has been selected for comparison. Finite element analyses method is employed to study the performance of the machines.

2 Machine topologies

The five machine topologies are shown in Fig.1. To maximize stator winding flux linkage and power density of the PM machine, the coil pitch should be as close to the pole pitch. Hence the slot numbers (N) and pole numbers (2p) should be differ by the smallest integer. When $2P = N$, this kind of motor is not realistic, Therefore the closest slot number and pole number combinations would differ only by one. However such machines exhibit unbalanced magnetic pull, and may result in excessive noise and vibration. So in practice the most appropriate slot and pole number are related by $2P = N \pm 2$. Typical similar slot and pole number combinations are 6 slot/4 pole, 6 slot/8 pole, 12 slot/10 pole, 12 slot/14 pole, 18 slot/16 pole, 24 slot/22 pole, 24 slot/26 pole, etc. In such machines either all the teeth or alternate teeth can carry a coil [3]. In this paper, we investigated 12 slot/10 pole and 12 slot/14 pole machines. The majority of parameters of the machines are identical apart from the slot and pole number combinations and their winding configuration. The parameters of machines are shown in Table 1.

3 Performance comparisons

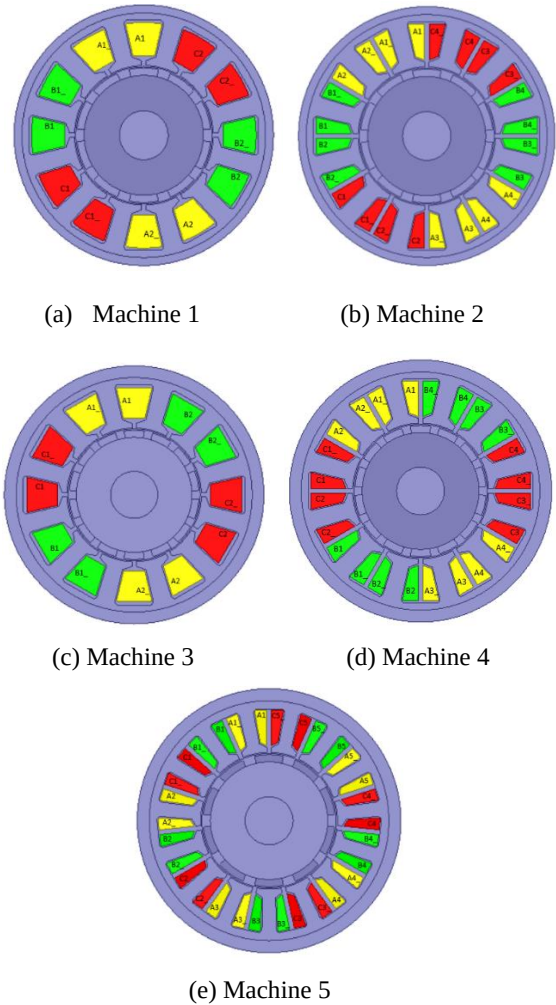
The analysis result of electromagnetic performance, in terms of the flux linkage, back EMF, winding inductances, cogging torque and electromagnetic torque are given in this part.

3.1 Flux linkage

A motor whose pole-pitch is almost equal to the slot-pitch is conducive to maximizing the flux

Table1: Parameter of machines

Machines No.	1、 2	3、 4	5
Number of poles	10	14	10
Number of slots	12	12	15
Stator outer diameter (mm)	100	100	100
Stator inner diameter (mm)	57	57	57
Rotor outer diameter (mm)	49	49	49
Slot opening(mm)	1.8	1.8	1.8
Air gap length (mm)	0.1	0.1	0.1
Stack length (mm)	50	50	50



- (a) Machine 1—12 slot/10 pole alternative teeth wound
(b) Machine 2—12 slot/10 pole all teeth wound
(c) Machine 3—12 slot/14 pole alternative teeth wound
(d) Machine 4—12 slot/14 pole all teeth wound
(e) Machine 5—15 slot/10 pole alternative wound

Figure1: Models and winding arrangement

linkage. The open-circuit flux linkage is given by[6]

$$\psi_{phase} = 2N_p l_a R_s \sum_{n=1,3,5}^{\infty} \frac{1}{np} f_{Brn} K_{dnp} \cos(np\theta) \quad (1)$$

Where N_p , l_a , K_{dnp} are the number of turns per phase, the active stator axial length, and the winding factor, respectively. The variation of the flux-linkage per phase is shown in Fig. 2. The 12 slot/10 pole motor has the maximum flux-linkage which is higher than 15 slot/10 pole and 12 slot/14 pole motors. And motors with alternative teeth wound have higher value than all teeth wound.

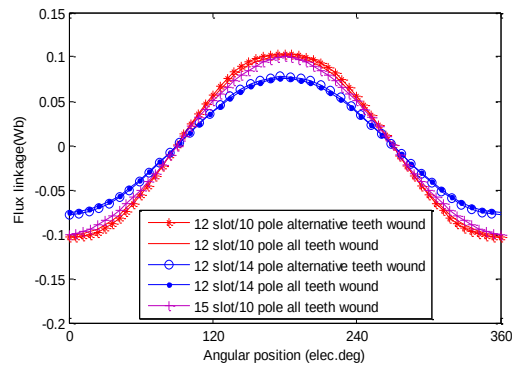


Figure 2: Comparison of the flux linkage for five machines

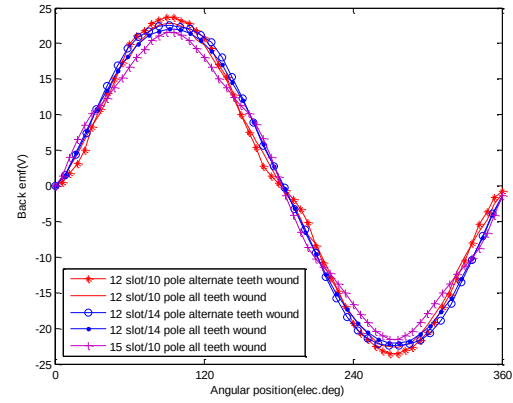
3.2 Back EMF

Stator current interacting with induced EMF harmonics can cause pulsating torque. So in the process of the electric motor design the harmonics should be minimize as possible to reduce the ripple torque. The induced harmonics are related to the winding arrangement and the air-gap magnetic field generated by magnets [5].

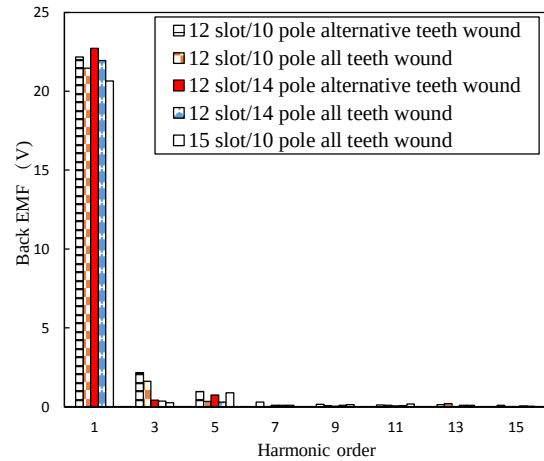
The no-load induced EMF and harmonic analysis of five motors are shown in Fig. 3 and the total harmonic distortion (THD) in Table 2. It was shown that the THD of 12 slot/10 pole machines are bigger than 12 slot/14 pole and 15 slot/10 pole machines. And at the same time we can know from the table machines with all teeth wound have lower THD than machines with alternative teeth wound, it is less about 25%.

Table 2: THD of five machines

Machines No.	1	2	3	4	5
THD (%)	11.0	8.3	4.7	3.5	5.1



(a) Phase back EMF waveforms



(b) Harmonics spectra

Figure 3: Comparison of the back EMF for five machines

3.3 Winding inductances

As shown in Table 3 different winding arrangements has a great influence on machine inductances. Machines with similar slot and pole number (12 slot/10 pole and 12 slot/14 pole motors) have a higher self-inductance and a lower mutual-inductance compared with machine which has a conventional slot and pole number combination (15 slot/10 pole). It is obvious that the self-inductance of machines in which alternative teeth are wound is higher than machines with all teeth are wound. On

Table 3: inductances (mH)

Machines	Self-inductance	Mutual-inductance
1	12.53	0.1010
2	8.33	0.9119
3	12.99	0.0463
4	8.64	0.9412
5	4.47	2.1380

the contrary the mutual-inductance is significantly smaller. And this superiority for 12 slot/14 pole machine whose pole number is higher than slot number is more remarkable.

3.4 Cogging torque

For fractional slot motor, the higher is the smallest common multiple between the slot and pole numbers the smaller is the cogging torque. The values of the motors investigated in this paper are 30, 60, 84 for 15 slot/10 pole, 12 slot/10 pole, 12 slot/14 pole respectively. The results by finite element analyses are shown in Fig.4. As expected, the cogging torque of 12 slot/14 pole motor is the minimum, and motor either with alternative wound or all teeth wound, the value is almost identical.

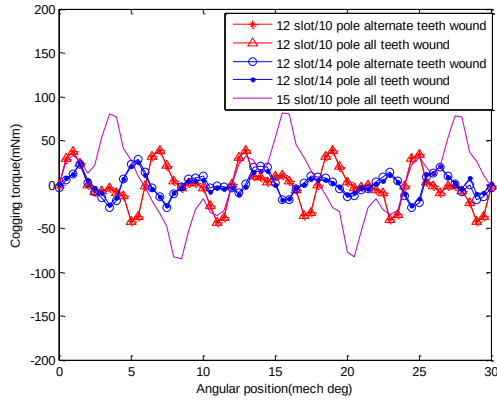


Figure 4: Comparison of the cogging torque for five machines

3.5 Electromagnetic torque

The electromagnetic torque can be calculated by[3]

$$T = \frac{1}{\omega_r} (e_a i_a + e_b i_b + e_c i_c) \quad (2)$$

Where e_a , e_b , e_c , i_a , i_b , i_c are the back EMFs and currents in phases A, B and C respectively. When the machines investigated in this paper are supplied with sinusoidal current. The output torque waveforms predicted by finite element are shown in Fig 5. Clearly, machines with alternative teeth wound have a higher torque capability it is identical for 12 slot/10 pole and 12 slot/14 pole motors. When come to slot and pole number combination, 12 slot/14 pole machines have a higher torque capability. So the 12 slot/14 pole motor with alternative teeth wound has the highest value, however machine with all teeth wound exhibits a lower torque ripple 1.48% compared 2.47% for alternative teeth wound machine.

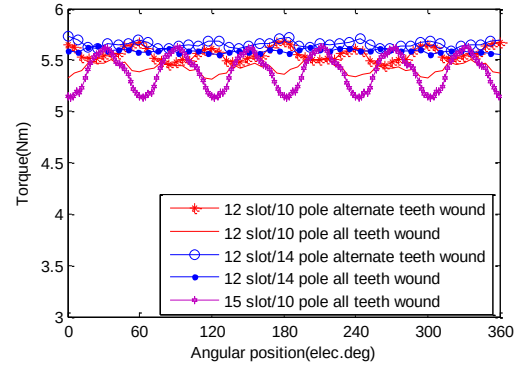


Figure 5: Comparison of the Output torque for five machines

4 Conclusion

12 slot/10 pole and 12 slot/14 pole permanent magnet motors, for the application of electric vehicles traction, whose slot number and pole number differ by two were investigated and their performance were compared with either all the teeth or alternate teeth are wound. It was shown that they each have their own advantages and disadvantages. In terms of slot and pole number combination, 12 slot/10 pole motor has the maximum flux-linkage and 12 slot/14 pole machine has higher electromagnetic torque, lower cogging torque and torque ripple. When come to winding arrangement, the THD of machines with all teeth wound are smaller, and machines in which alternative teeth are

would have higher self-inductance and lower mutual-inductance then result of higher fault tolerance. For all the four kinds of machines employing non-overlapping concentrated stator windings, they would be more economical. When designing a machine, both the advantages and disadvantages should be taken into consideration to meet the design requirement.

Acknowledgement

This work was supported by the Fundamental Research Fund for the Central Universities of China (Grant No. 2014MS95)

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Authors



Aimeng Wang, Ph.D. degree, professor of North China Electric Power University. She has been engaged in design and drive system of permanent magnet machine.



Lijuan Chang, Master degree, study in North China Electric Power University. Her research interest in permanent magnet machine design and optimization.



Shuhui Dong, Master degree, teacher of North China Electric Power University. Her research interest in new energy wind power generation.