Effect of Multi-Phase Windings on Fraction-Slot Concentrated-Winding Permanent-Magnet Machine for Low Space Harmonics

Junqiang Zheng, Jinghua Ji, Mei Kang, Xunhui Zhu

School of Electrical and Information Engineering, Jiangsu University, Zhenjiang 212013, China

Presented at the MT-25
RAI – Amsterdam
Session number: Mon-Af-Po1.04-20 [50]
Program I.D. number: 283
2017 Aug. 28 (Mon) 13:15

Abstract

One of the key challenges of utilizing fraction-slot concentrated winding (FSCW) in permanent-magnet (PM) machine is high eddy-current loss in magnets due to the abundant space harmonics in stator magneto-motive force (MMF). These MMF harmonics also result in other undesirable effects, such as localized saturation, vibrations and noise. In this paper, the relationship between multi-phase windings and stator MMF harmonics is investigated. An analytical equation is derived to explain why the appropriate multi-phase windings can eliminate some MMF harmonics. Finally, three FCSW-PM machines, namely the 3-phase one, the 6-phase one and the 12-phase one, are designed and their stator MMF harmonics, torque, PMs eddy-current loss, radial force density harmonics, demagnetization risk and thermal distribution are comparatively analyzed. The results verify the theoretical analysis.

introduction

RECENTLY, permanent-magnet (PM) brushless machines exhibits high torque density, small volume and high efficiency, which have been gaining interest in many fields such as electric vehicle, wind power generation and aerospace [1], [2]. Also, the fractional-slot concentrated-winding (FSCW) has been extensively investigated. The photograph of 3-phase and 4-phase FSCW configurations is presented in Fig. 1. It has been known that the FSCW provides high fault-tolerant performance, short non-overlapping end winding, high slot fill factor, sinusoidal back-EMF and good flux weakening capability [3]. However, one of the key challenges of utilizing FCSW-PM machines is abundant space harmonics in the stator magneto-motive force (MMF). These stator MMF harmonics will result in some undesirable effects, such as irreversible demagnetization of PMs, acoustic noise and vibrations, and the localized core saturation [4].

A large number of methods have been employed to reduce/eliminate MMF harmonics in literatures. Adopting non-uniform tooth width, using asymmetric number of turns, and applying phase shift by doubling slot numbers have been reported in [5]-[7]. However, these methods compromise the performance and the manufacture advantage of concentrated-windings. A delta-star connection was utilized to reduce sub-harmonics in [8]. However, its shift angle is restricted to 30°, 150° and 270°. Special magnetic flux barriers in stator yoke were introduced in [9] to reduce sub-harmonics. Nevertheless, the mechanical stiffness of the stator is reduced significantly with presence of the flux barriers. Multiple 3-phase set with an appropriate phase shift between them have been devised to cancel out the undesirable MMF harmonics [10]. However, this approach leads to an overlapping windings configuration, compromising advantages of the concentrated-winding.

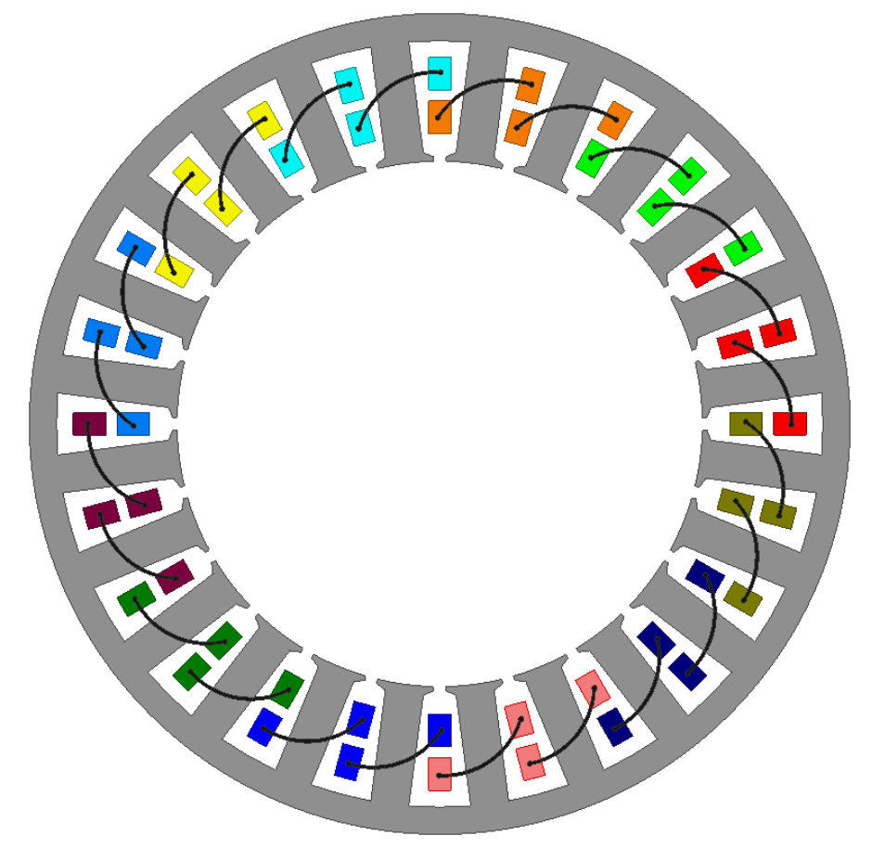
In order to reduce or eliminate these undesirable stator MMF harmonics while retain the advantages of FSCW, the multi-phase windings configuration will be studied in this paper. Firstly, the relationship between multi-phase windings configuration and stator MMF harmonics is studied. An analytical equation is derived to explain why the multi-phase concentrated-winding can eliminate some stator MMF harmonics. Then, a 12-phase 24-slot and 22-pole FSCW-PM machine is designed, as compared with the 3-phase and 6-phase ones. Furthermore, the MMF harmonics, torque, eddy-current loss, radial force harmonics, demagnetization risk and thermal distribution are comparatively analyzed for evaluation.

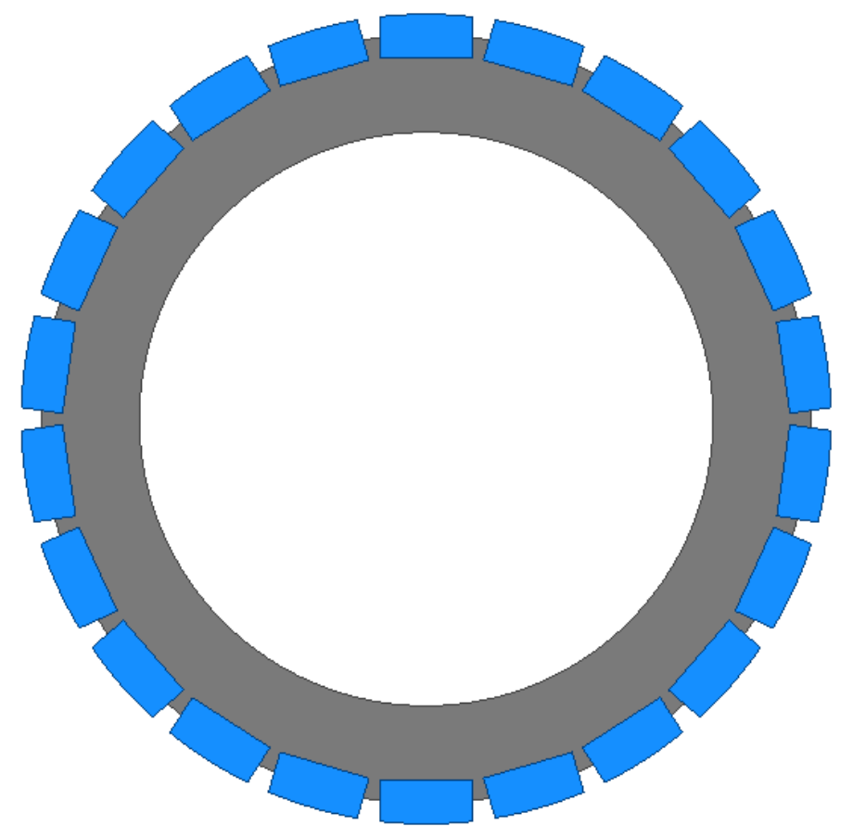

9s6p FSCW-PM machine

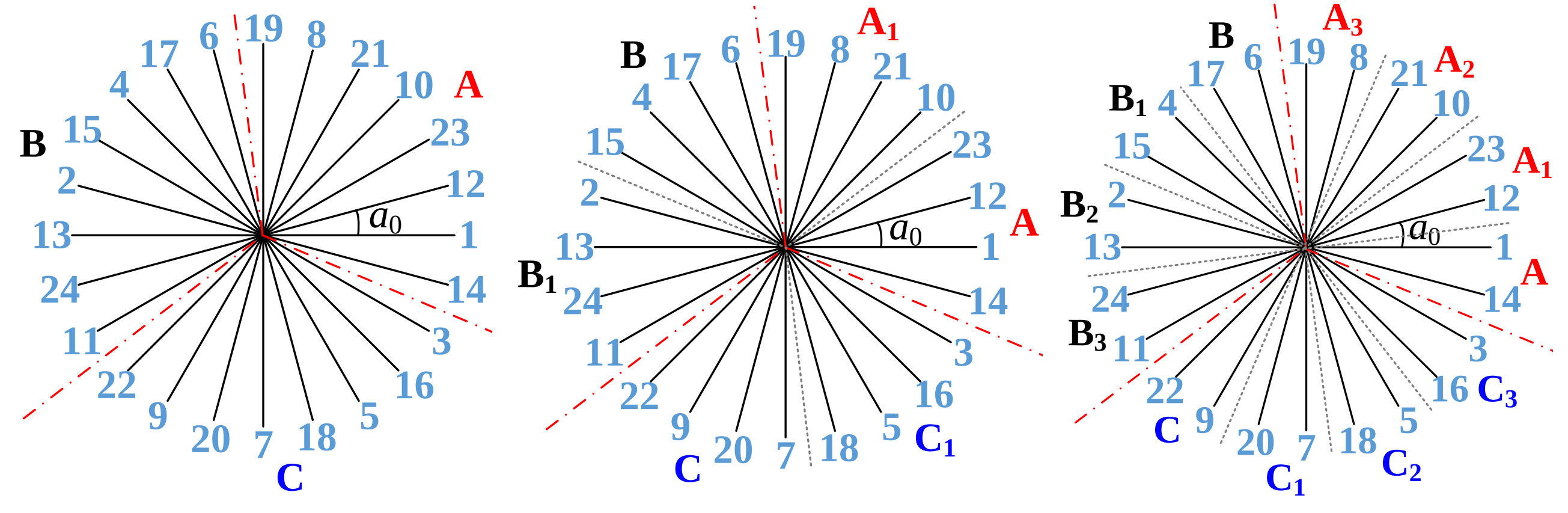

8s6p FT-PM machine

Topology and feature

Fig. 2 exhibits the designed 12-phase 24-slot and 22-pole FSCW-PM machine. In order to obtain good electromagnetic performances, it has been comprehensively optimized. The stator topology and 12-phase FSCW configuration is shown in Fig. 2(a). The FCSW can greatly reduce the end winding, improve the independence of interphase and be easy to decoupling control. In addition, the stator MMF harmonics is significantly reduced and the freedom of control is improved by adopting 12-phase windings. The surface-insert PM rotor structure is depicted in Fig. 2(b). It can be observed that in the surface of rotor yoke, a dovetail groove structure is designed to enhance mechanical robustness. The sleeve with high conductivity can be omitted and greatly reduce the rotor eddy-current loss. Besides, it can be found that the whole rotor has a relatively small volume to obtain good dynamic response characteristics. Fig. 3 presents their slot potential star diagram and adopts 60 deg phase spread. In slot potential star diagram, a_0 is the slot-pitch mechanical angle. The parameters of the 12-phase FSCW-PM machine are listed in Table II.


Stator of 12-phase FSCW-PM machine


Rotor of PM machine



3-phase
6-phase
12-phase
Slot potential star diagram

Analysis

It can be assumed that *m*-phase windings are symmetric and each phase windings has the same number of turns. Also, the axis of the phase-A is aligned with the *d*-axis.

$$\begin{aligned}F_v(\theta,t)=&\frac{1}{2}N_v I\{[\cos(pwt-v\theta)+\cos(pwt+v\theta)]\\&+[\cos(pwt-v\theta-(v+1)\frac{2\pi}{m})+\cos(pwt+v\theta+(v-1)\frac{2\pi}{m})]\\&\qquad\vdots\qquad\qquad\qquad\vdots\\&+[\cos(pwt-v\theta-(v+1)\frac{2(m-1)\pi}{m})+\cos(pwt+v\theta+(v-1)\frac{2(m-1)\pi}{m})]\}\end{aligned}$$

It can be seen that only vth order MMF harmonics exist in an m-phase FSCW by

$$v\pm1=km$$

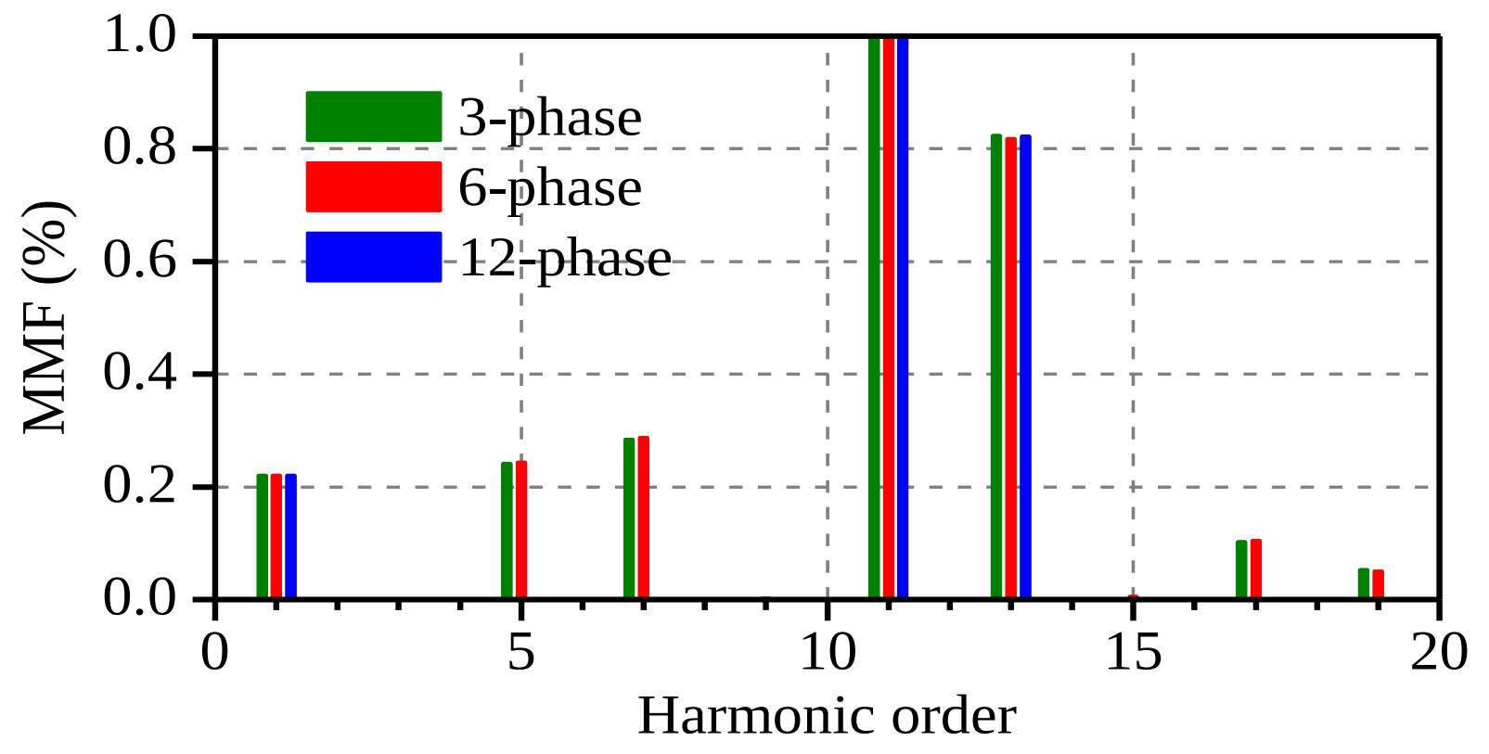
where k is ±1, ±2, ±3…. So, all stator MMF harmonics (except v=mk±1 orders) are eliminated by adopting multi-phase windings. Obviously, the orders of the eliminate harmonics are directly related to the phase number. It can be concluded that with increase of the phase number, harmonics content of stator MMF is reduced. Table I exhibits the stator MMF harmonics orders in 3-phase, 6-phase and 12-phase FSCW configurations. It should be noted that the red font represents orders of elimination harmonics by symmetrical even-slot stator structure.

Thus, it is well explained that the 3-phase and 6-phase windings have same stator MMF harmonic orders. Since the distribution effect of the windings is reduced with increase of phase number, the 12-phase windings have the fewest orders of stator MMF harmonic.

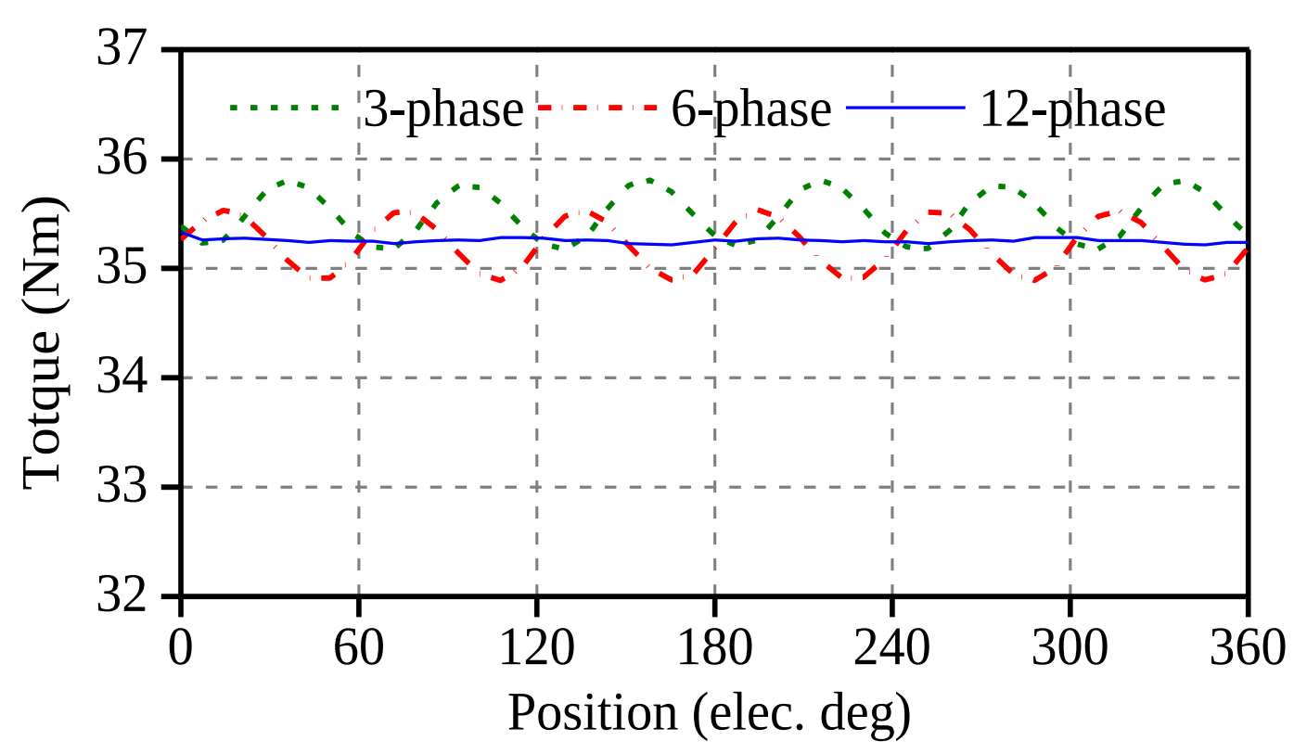
TABLE I
MMF HARMONIC ORDERS IN DIFFERENT PHASE NUMBER

	3-phase	6-phase	12-phase
MMF harmonic	v=3k±1	v=6k±1	v=12k±1
All harmonic	1,2,4,5,7,8,10,11,13,14,16,17,19,20,22,23,25,	1,5,7,11,13,17,19,23,25	1,11,13,23,25
Even slot	1,5,7,11,13,17,19,23,25	1,5,7,11,13,17,19,23,25	1,11,13,23,25

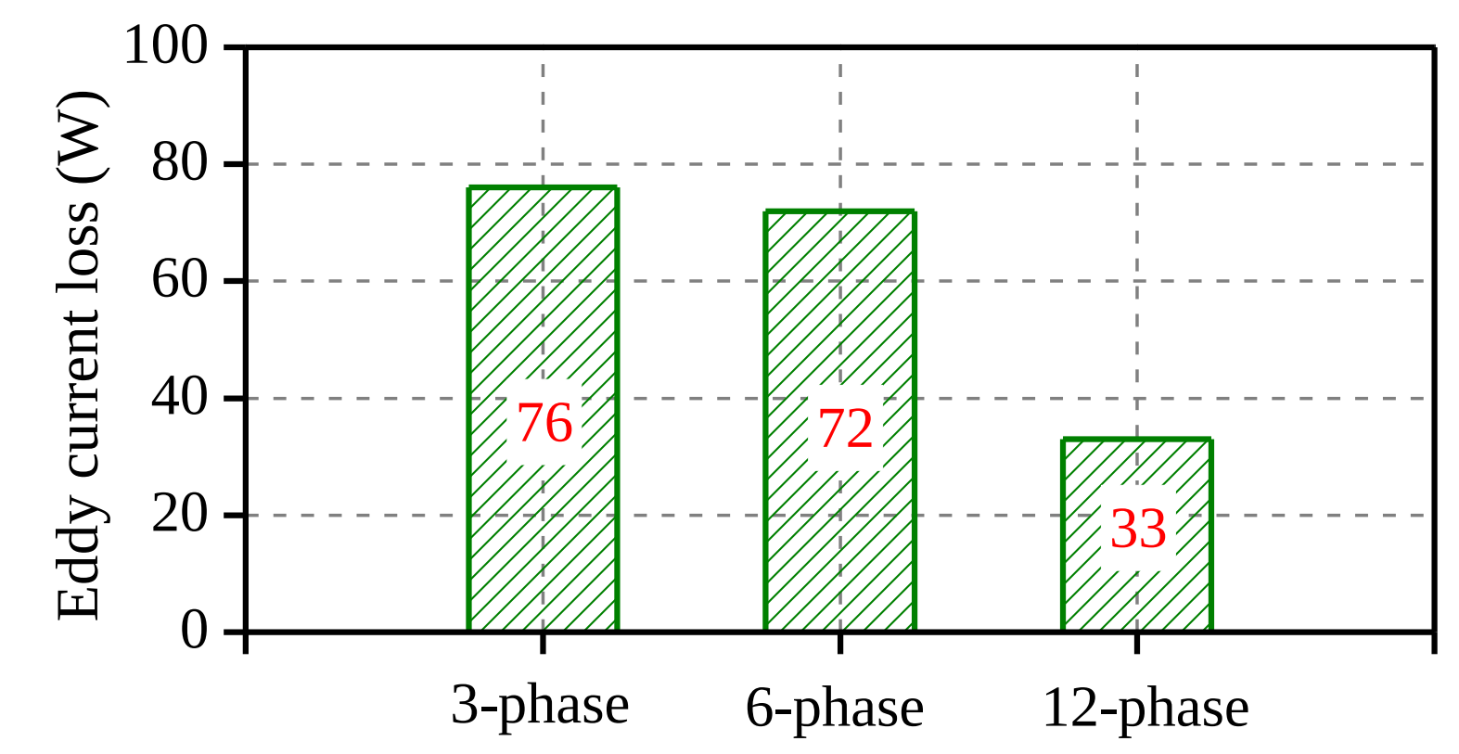
Performance



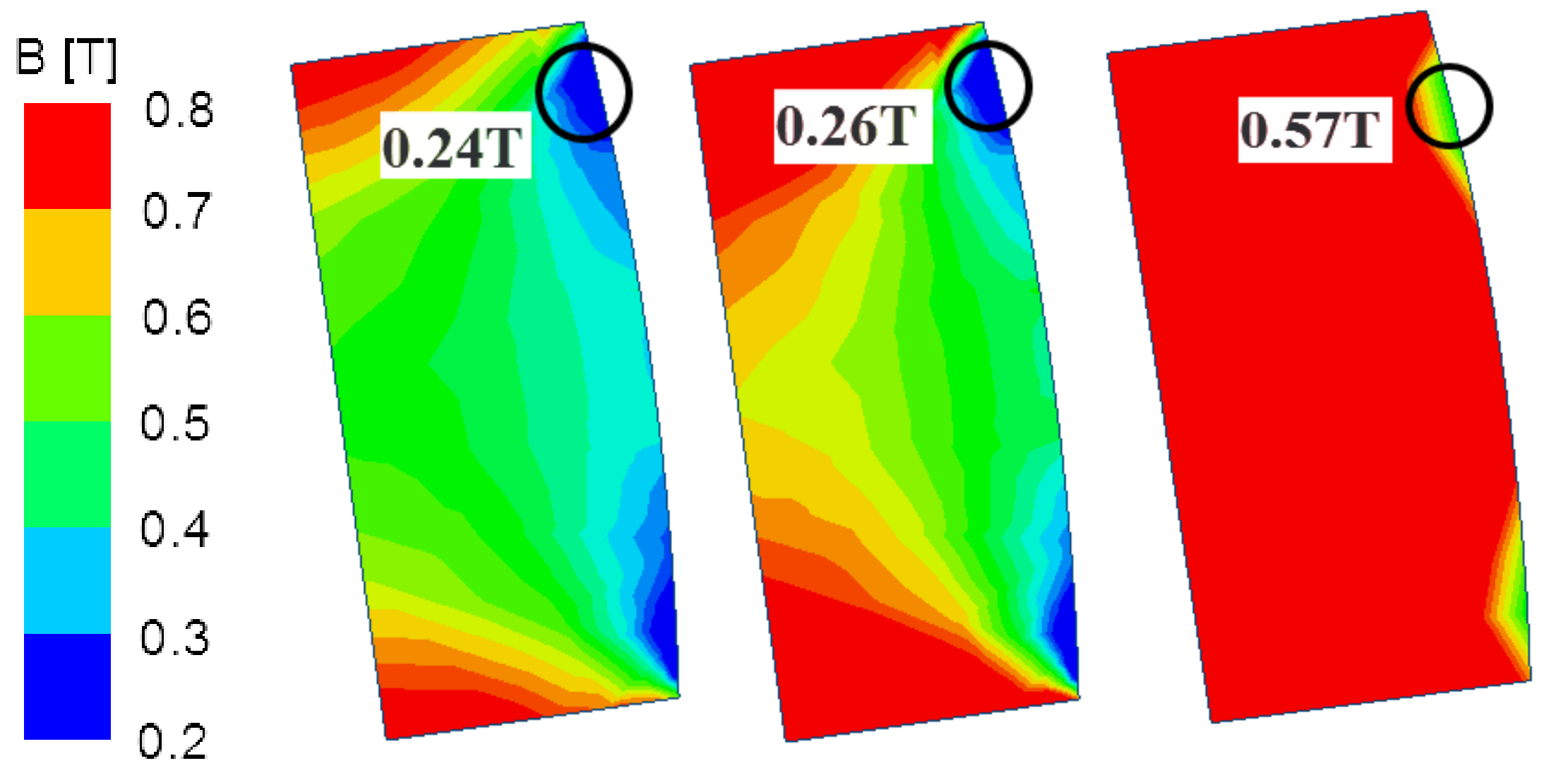
Normalized MMF harmonics distribution



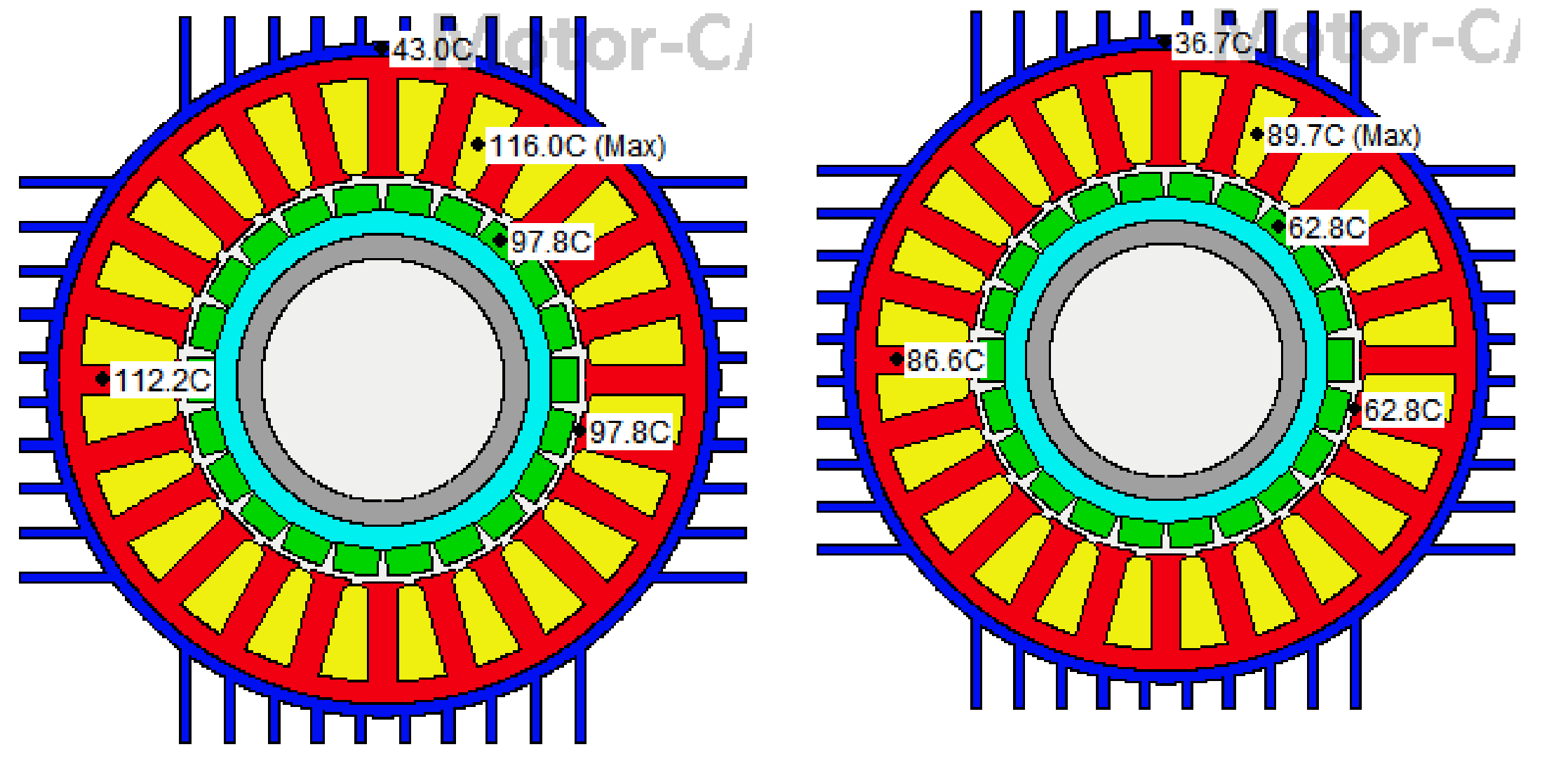
Electromagnetic torques



Electromagnetic torques



Magnetic field nephogram of the PM at overload operation condition



Temperature distribution of radial of both FSCW-PM machines

Conclusions

In this paper, the influence of multi-phase winding on stator MMF harmonics has been investigated. An analytical equation for FSCW is derived to reveal the relationship between stator MMF harmonics and phase number. It can be concluded that with the increase of phase number, stator MMF harmonics is reduced. Meanwhile, three FSCW-PM machines with different phase numbers have been compared by using FEM. The result shows that the machine with higher phase number has less stator MMF harmonics, low torque ripple and low PMs eddy-current loss. Besides, with the increase of phase number, the radial force density harmonic, the magnets demagnetization risk and the thermal distribution can also be reduced.