The Journal of Engineering

The 9th International Conference on Power Electronics, Machines and Drives (PEMD 2018)

Novel 24-slots14-poles fractional-slot concentrated winding topology with low-space harmonics for electrical machine

eISSN 2051-3305
Received on 22nd June 2018
Accepted on 27th July 2018
E-First on 16th April 2019
doi: 10.1049/joe.2018.8085
www.ietdl.org

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Abstract: This paper proposes a novel winding layout for the electric machines with fractional-slot concentrated windings (FSCW) using a stator shifting concept, with which all the non-working harmonics can be completely cancelled or significantly reduced and the non-overlapping winding can be kept. First, the basic winding layout with a 24-slot 14-pole machine to reduce the significant 1st sub-harmonic will be presented for machines with single-layer (SL) windings. From this, a novel double layer (DL) winding layout using the stator-shifting concept will be introduced. By adopting two SL winding sets with a 105° mechanical angle shift with respect to each other, it is not necessary to use overlapping windings. With this configuration, the 1st sub-harmonic will be completely cancelled and the parasitic 5th harmonic will be significantly reduced. Hence, the rotor losses, specifically magnet loss will be significantly reduced. Finally, two PM machines with different DL winding layout, namely, conventional 12-slot 14-pole and 24-slot 14-pole machine, will be designed and compared to validate the advantages of this winding topology.

1 Introduction

The fractional-slot concentrated winding (FSCW) permanent magnet motor is a potentially excellent candidate for both aerospace applications and electric vehicles (EVs) due to its high reliability and good fault-tolerance [1, 2]. However, one of the key challenges is the significant space harmonics in the armature MMF distribution including sub- and high-order harmonics, which may result in localised saturation, eddy current loss in magnets (rotor losses), and unbalanced magnetic force inducing noise and vibration [1, 3].

A number of methods like multi-layer winding, stator shifting, and unequal coil numbers have been proposed to deal with this in recent times. The impact of layer numbers on the performance of surface permanent magnet (SPM) synchronous machines has been studied in [4], which suggests the double-layer (DL) configuration features less harmonic content and consequently lower torque ripple, but a weaker overload capability compared to single-layer (SL) counterpart. In [5, 6], the method of four-layer winding or three-layer winding has been proposed to reduce or even cancel some particular harmonics by shifting a specific mechanical angle between first and second winding sets and specifically in [6] the effect of four-layer winding on the PM eddy-current loss and vibration/noise have been identified as well. Another method of using concept of stator shifting was introduced by Dajaku [7] with doubling the slot numbers. With this method associated with unequal coil numbers, almost all the harmonics have been cancelled, but the winding is no longer non-overlapped due to the coil pitch of two slots [7–9]. However, as far as the authors' knowledge, the first use of this method to cancel all the low-order space harmonics was presented for a linear induction motor in [10, 11].

However, for either the method of four-layer winding or the conventional stator shifting, it is believed that mutual inductance will be considerably higher since there are two coils belonging to different phases wound around a tooth for a four-layer winding design, and there are overlaps of different phase windings for the method of conventional stator shifting. In addition to that, doubling slot numbers with overlapping windings (coil pitch of 2 slots) or using four-layer windings and unequal coil numbers complicate the manufacturing process and can negatively affect the slot fill factor.

Here, an improved winding layout based on the 24-slot 14-pole PM motor is presented to deal with these challenges by using stator winding shifting and multi three-phase winding sets, but without using an overlapping winding. With this new winding layout, the 1st sub-harmonic has been completely cancelled and the parasitic 5th harmonic has been significantly reduced. In order to validate the proposed winding layout, two PM machines with different DL winding layout, namelt, conventional 12-slots/14-poles and 24-slots/14-poles, will be designed and compared, with particular regard to the losses and output torque.

2 Basic winding layouts

The FSCW machine incorporates significant MMF harmonics due to its non-sinusoidal windings. This is especially serious for machines with a SL winding which has two opposite coils on each side. A significant 1st sub-harmonic will be induced and its magnitude may be even higher than that of working harmonic [3]. For example, 12-slot 14-pole machines with both SL and DL winding configurations are shown in Fig. 1 and their corresponding stator MMF spectra and harmonic distributions are illustrated in Fig. 2.

For the 14-poles machine here, the only working harmonic is the 7th, so the 1st, 5th, 11th, and 13th etc. are undesired harmonics. These non-working harmonics will result in torque ripple, rotor loss, and localised saturation, which is undesirable for the machine. It should be noted that the working harmonic can be the 5th for a 10-pole machine. It can be observed from Fig. 2*b* that a significant 1st sub-harmonic has been generated by the SL winding configuration, while the DL winding design can reduce the 1st sub-harmonic.

In fact, it is also apparent from Fig. 2*a* that a significant 1st sub-harmonic is obvious in the MMF distribution of SL winding design. The inherent reason under this phenomenon is the two opposite coils of each winding are distributed on the opposite side of the machine, which means the magnetic flux induced by one coil have to be closed by another opposite coil through a very long magnetic flux path. In order to deal with the problem of significant 1st sub-harmonic for the machines with SL winding configuration, a new type of machine with two opposite coils of each phase being distributed adjacent has been proposed [12, 13], which results in

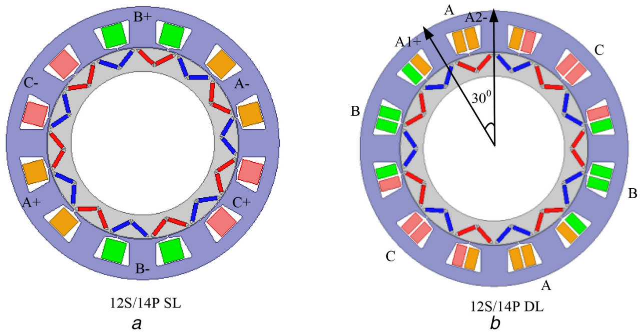

Fig. 1 *Conventional winding layouts for 12slots/14poles machine*
(a) Single layer, ***(b)*** Double layer

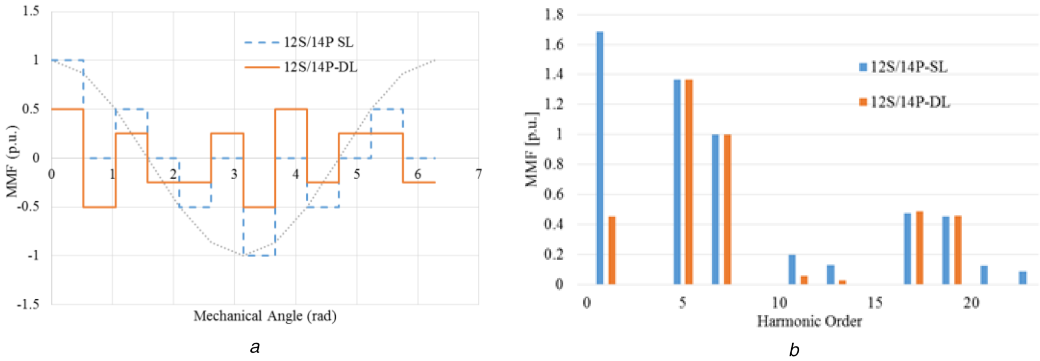

Fig. 2 *Stator MMF harmonics distribution for 12Slots/14poles machine*

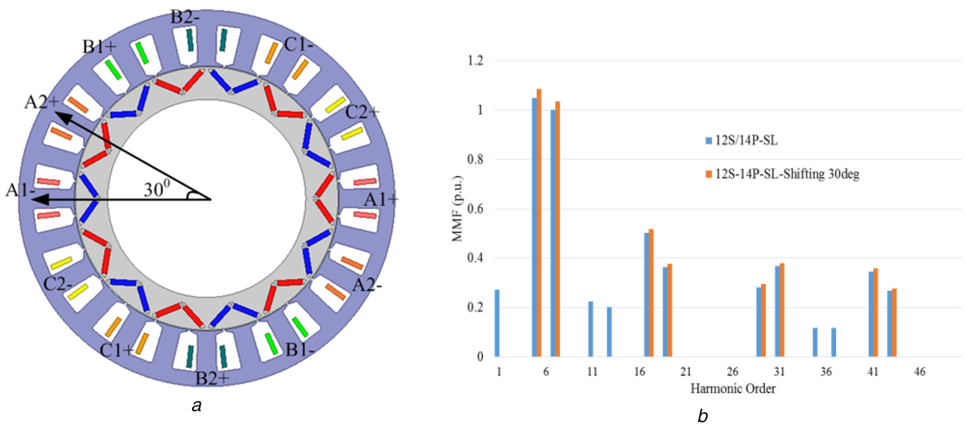

Fig. 3 *24Slots/14Poles machine with single layer winding*

the flux generated by one coil can be closed in a short flux path through an adjacent opposite coil, as shown in Fig. 3*a*. This is a 24-slots/14-poles machine with SL winding derived from 12-slots/14-poles with SL winding. The Fourier analysis of the MMF spectrum of this configuration is shown in Fig. 3*b*. It can be observed that the MMF harmonic distribution is quite similar to 12-slots 14-poles with DL winding and the 1st sub-harmonic has been considerably reduced with this winding configuration. However, there are still many harmonics in the stator MMF distribution. In addition, a negative effect of this is the pitch factor that has been reduced as well since the pole number is much lower than the slot number and this correspondingly will lead to a lower winding factor. Winding factor is related to torque output, so generally a lower winding factor will lead to a lower output torque, though this is not always the case.

3 New winding layout with low harmonic content

Machines with FSCW configuration have many advantages but in order to use them, it is necessary to avoid the disadvantage of significant MMF harmonics. Therefore, in this section, methods to reduce or even cancel the non-working MMF harmonics will be studied.

3.1 Cancellation of the 1st sub-harmonic

Fig. 3 shows the 24-slot 14-pole motor with a three-phase SL winding. The MMF distribution of this configuration can be expressed as Fourier series.

$$F(\theta, t) = \sum_{k = 1, -5, 7}^{\infty} v_k \sin\left(k\theta - wt - \frac{k\pi}{24}\right) \tag{1}$$

$$vk = \frac{12NI}{k\pi}\sin\left(\frac{k\pi}{24}\right)\sin\left(\frac{k\pi}{24}\right) \tag{2}$$

where v_k is the amplitude of kth order MMF space harmonic; k is the MMF harmonic order; N is the number of turns of each coil; I is the RMS value of current; θ is the space angle; w is the angular speed.

It can be observed that the two adjacent coils for each phase winding have a mechanical phase difference in space by 30°, of which corresponding electric angle is equal to 30° as well (30 × 7–180). Thus, a possible winding configuration is a dual three-phase windings (ABC&A1B1C1) with phase shifting to each other in

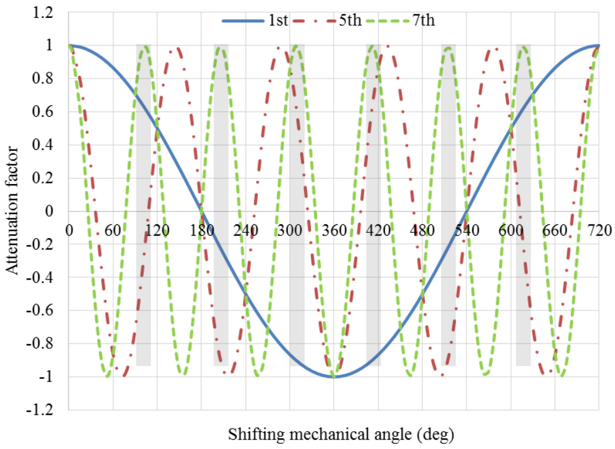

Fig. 4 *Attenuation factor for different order MMF harmonics*

time by 30°. The MMF distribution under the dual three-phase configuration can be written as Fourier series as well.

$$F_d(\theta, t) = \sum_{k = 1, -5, 7}^{\infty} v_{dk} \sin\left(k\theta - wt - \frac{k-1}{12}\pi\right) \quad (3)$$

$$v_{dk} = \frac{12NI}{k\pi} \sin\left(\frac{k\pi}{24}\right) \sin\left(\frac{k-1}{12}\pi\right) \quad (4)$$

where v_{dk} is the amplitude of kth MMF space harmonic.

From (4), the amplitude of each MMF space harmonic including an item of $\sin(((k-1)/12)\pi)$ is different from that of the one 3-phase winding set. When $k = 1$, namely the 1st sub-harmonic, the amplitude of the 1st MMF space harmonic v_{d1} is equal to 0, which means the 1st sub-harmonic has been completely cancelled. Moreover, when k equals to −11 or 13, their corresponding amplitudes are 0 as well. In fact, all the $(12k \pm 1)$ order harmonics have been cancelled. One thing that should be noted is that the rotational direction of $(12k - 1)$ or $(6k - 1)$ order harmonic is different from the working harmonic. The MMF space harmonics under this condition are presented in Fig. 3*b*. As can be seen, with dual three-phase configuration, the 1st sub-harmonic is completely cancelled while the working harmonics (either 5th or 7th) are improved by 3.6% at the same time compared to the one 3-phase winding configuration. On the other hand, the 11th, 13th, 23rd, 25th, 35th, 37th are cancelled as well. These are in accordance with the above theoretical analysis from the Fourier series. Thus, the dual three-phase winding set configuration is a good method to cancel the 1st MMF sub-harmonic.

However, the parasitic harmonics are not being reduced, but increased like the working harmonic. Hence, the method to reduce or cancel the parasitic harmonic has to be studied.

3.2 Reduction of parasitic harmonics

There are parasitic harmonics in the machines with FSCW like 5th and 7th for 12-slots 10-/14-poles machine. They usually occur in pairs, e.g. 5th and 7th, which result in difficulty to reduce only one of them. For example, for the 24-slot 14-pole machine, the working harmonic is 7th, but the parasitic 5th harmonic exists as well, its amplitude is quite similar to that of 7th working harmonic, and their corresponding winding factors are exactly the same.

A method of utilising the concept of 'stator shifting' has been proposed in [7], with which the number of stator slots is doubled and this means the coil pitch has been changed from 1 slot to 2 slots, then another identical winding set is added to the same stator, but there is a certain mechanical shift angle between these two winding sets. In order to cancel the parasitic harmonic, the windings usually overlap each other, namely, a distributed winding with short pitch, which is undesirable for manufacturing and/or the fault-tolerant machine design.

In this section, by utilising the concept of stator shifting, the parasitic harmonic can be considerably diminished or completely cancelled without using an overlapping winding. One thing that should be noted is the pitch factor might be lower compared to previous design, and this will result in a lower winding factor if the distribution factor holds the same. The process of realising the stator shifting based on a 24-slot 14-pole machine with SL winding is as follows:

(a) Using the 24-slot 14-pole machine with a dual three-phase SL winding proposed in section 2 as a base.
(b) Another dual three-phase winding is added, whose coil distribution is the same as the first dual three-phase SL winding set, but with a specific mechanical shift angle between these two winding sets.
(c) The stator and rotor remain the same; and these two winding sets are connected in series.

From (4), the amplitude of each harmonic can be obtained. If there is a specific mechanical angle α between the two winding sets, the resulting amplitude of each harmonic after the two winding sets added together can be written as

$$v_{\alpha dk} = v_{\alpha dk} \cos\left(\frac{k\alpha}{2}\right) \quad (5)$$

It can be observed that an additional factor of $\cos(k\alpha/2)$ has been added to the amplitude of each MMF harmonic. To simplify the analysis, this factor is defined as 'attenuation factor'. For each harmonic, namely a given k, with different shifting mechanical angle α, the attenuation factor will be varied sinusoidally. However, it should be noted that the mechanical angle α is not varying continuously but will be stepwise, as the winding sets can only shifted between slots. Thus, α is equal to $j \times 360°/z$, where j is a non-negative integer and z is the stator slot numbers. In this case, each slot corresponds to an angle 15° (360°/24), so the mechanical angle of α can only be $j \times 15°$. Therefore, with an appropriate shifting angle of α, the attenuation factor of a specific harmonic or more harmonics can be reduced or cancelled without influencing the desired working harmonic.

The attenuation factor for each order harmonic can be calculated according to (6) and summarised in Fig. 4. As can be seen, for different order harmonics, their attenuation factor changed sinusoidally with different periods; kth order harmonics vary at a period of $k/2$, which is in accordance with the above analysis.

In the case of a 24-slot 14-pole machine with dual three-phase windings, the working harmonic is chosen as the 7th harmonic and the main parasitic harmonic is the 5th harmonic. Therefore, it is necessary to find out an appropriate angle to reduce or cancel the 5th harmonic while having no or not much negative influence on the 7th harmonic. It can be observed from Fig. 4, possible or feasible angle area is represented by the grey areas, in which the attenuation factor of the 7th harmonic is almost equal to 1. Within these areas, the angle of 105° is a good candidate, at which the attenuation factor of 7th is 0.9914 while the attenuation factor for 1st and 5th is 0.6087 and −0.1305, respectively. This means the 5th harmonic has been effectively reduced and there are no considerably negative influences to the working harmonic (7th). The 1st harmonic does not need to be considered as it has been cancelled by using the dual three-phase winding configuration.

In fact, there is another angle of 108°, better than the 105° in terms of reducing 5th harmonic, because the fifth-order harmonic is completely cancelled under this shifting angle. However, this angle is not feasible for this design as the shifting angle can only be implemented in steps of $j \times 15°$. Therefore, the best candidate of shifting angle is 105°, which is corresponding to 7 slots for a 24-slot 14-pole machine.

Fig. 5 illustrates a proposed stator shifting concept in the designs of a 24-slot 14-pole motor with dual three-phase winding sets. Since the DL winding and SL winding can be recognised as all teeth wound and alternate teeth wound windings, the concentrated windings can be expressed by the corresponding teeth, namely, each tooth represents a corresponding wound concentrated winding coil. Two identical dual three-phase winding sets are adopted with the second three-phase winding set shifting

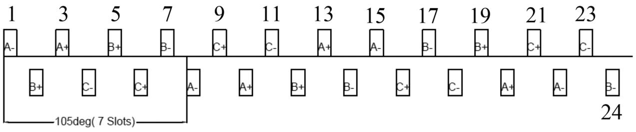

Fig. 5 *Concept of 'stator shifting' based on a 24 slot 14 pole machine*

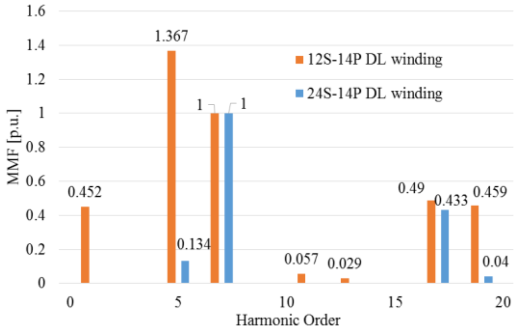

Fig. 6 *MMF distribution of two winding layout*

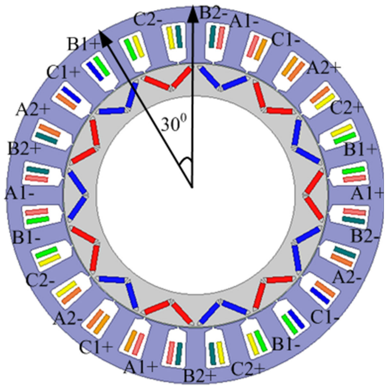

Fig. 7 *New configuration of 24S-14P with double layer winding*

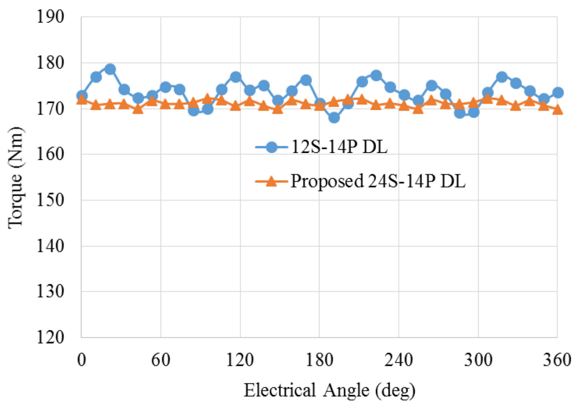

Fig. 8 *Comparison of torque performances between two machines*

105° (7slots) over the first winding set. This winding layout is using the concept of stator shifting but without adopting overlapping winding (coil pitch of two slots) that are usually used in conventional stator shifting [7, 8], since the coil pitch is not changed. Without overlapping winding coils, the effect of physical contact and larger mutual inductance could be avoided, which is preferable for fault-tolerant drive applications.

It is clearly from Fig. 6 that the 1st sub-harmonic is completely cancelled and the 5th harmonic is significantly reduced to 13%, and these two harmonics principally determine the rotor losses (magnet eddy current loss). Therefore, the magnet eddy current loss can then be significantly reduced. The pitch factor of the 24S-14P configuration is about 0.793, which is 21.8% lower than that of 12S-14P configuration, to achieve an equivalent ampere turns, more coil turns should be used in the 24S-14P machine under the same current which will result in more copper loss in the

Table 1 Design specification of electric drive system

Design specification	Data
peak power	45 kW
rated power	22 kW
peak torque	170 Nm
maximum torque ripple	≤5%
based speed	2500 rpm
maximum speed	12,000 rpm
DC link voltage	600 V

slots. However, due to the doubling of the number of slots, the end winding length is reduced significantly, more importantly, the magnetic field distribution has been changed so that a larger reluctance torque could be produced. Besides, the distribution factor is improved by 3.5% by using dual three-phase winding set. Therefore, this should not have a big influence on the torque output of the proposed motor. This will be illustrated in the next section.

4 Design example of machine with new winding layout

In order to validate the theoretical analysis of the novel winding layout, two PM machines with different slot/pole combinations and winding layouts, namely, proposed 24-slot 14-pole and conventional 12-slot 14-pole, are designed and compared based on a powertrain drive system used for such as hybrid EV (HEV) or pure EV. The insert-pm (IPM) configuration is adopted as the rotor structure. The drive requirement used here is summarised in Table 1.

For both machines, the outer dimension limitation is the same, with an outer diameter of 285 mm and an axial length of 90 mm. In addition, the rotor dimensions and magnet thickness are kept the same.

Fig. 7 shows the proposed 24-slot 14-pole motor with novel dual three-phase winding layout, which can be regarded as a combination of two 24S-14P machines with a SL winding, with the winding set of the second 24S-14P SL machine shifting seven slots (105°) over the first machine.

The electromagnetic torque of both machines has been calculated, as shown in Fig. 8. It can be seen that both machines can generate an average torque of 170 Nm, meeting the design torque requirement, but the proposed 24S-14P dual three-phase machine features an approximately constant torque with a ripple of 1%, as the significant non-working harmonics resulting in torque pulsation have been cancelled or significantly reduced. The torque ripple of the conventional 12S-14P machine is about 8.8%, which is beyond the requirement. Although this can be diminished by stator skewing or staggered rotor poles, these methods will complicate the manufacturing process and increase the cost. In addition to that the average torque will be negatively influenced.

Fig. 9 summarises the losses in the machine's different parts and total loss for both topologies. It is shown that the copper loss of the proposed 24S-14P dual three-phase motor is slightly higher than that of conventional motor, which is reasonable since more coil turns are used due to the lower winding factor. Other than that the iron loss and magnet loss is much lower than that of the conventional 12S-14P motor, and total loss of the former is almost half that of the latter. Specifically, the magnet loss of conventional 12S-14P machine is about 1,148 W, whereas the magnet loss of the proposed motor is only 60.8 W, significantly decreasing thermal load in the rotor part, which consequently reduces the demagnetisation risk to the magnets without using any additional methods like magnet segmentation or staggered rotor poles which may result in increasing manufacturing costs and/or negative influences on EM performance and mechanical stiffness. The efficiency of the proposed 24S-14P machine is 96.3%, while for the conventional 12S-14P machine, it is about 93.7%, showing that the proposed machine has a significantly higher efficiency.

As mentioned before, the winding factor of the proposed machine is lower than that of conventional 12S-14P machine, but their average torque is almost the same. This is because a larger

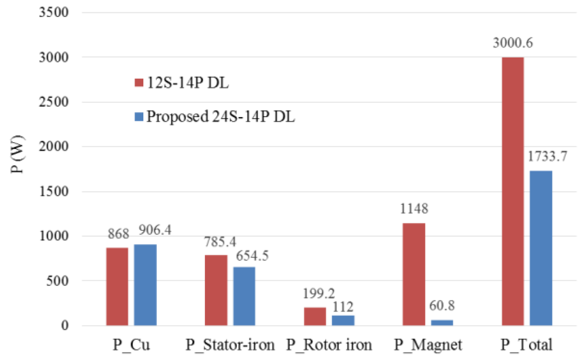

Fig. 9 *Comparison of output performances between two machines*

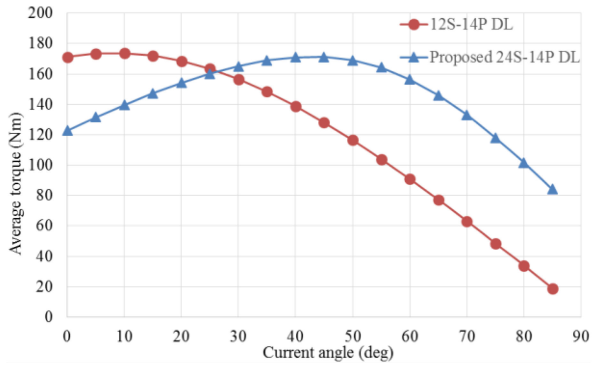

Fig. 10 *Average torque versus current angle*

reluctance torque is generated for the proposed machine, while there is not much reluctance torque for conventional 12S-14P machine. The average torques versus current angle for both machine is calculated and illustrated in Fig. 10. It is apparent that the maximum torque per ampere (MTPA) is 45° for the proposed machine and the corresponding torque is much higher than the torque when $i_d = 0$ control strategy is used. For the conventional machine, the MTPA is 5°, and the corresponding torque is just slightly higher than the torque when $i_d = 0$ control strategy is used.

Therefore, the proposed 24S-14P machine with a dual three-phase winding system is a promising solution to the challenges of high space harmonics for FSCW motors.

5 Conclusions

A novel 24 Slot 14 Pole DL winding layout using stator shifting method for FSCW permanent magnet motors was proposed, which gives complete cancellation of the 1st sub-harmonic, and significant reduction of the 5th sub-harmonic. Unlike the conventional stator shifting concept that normally requires overlapping coils, this novel winding layout can still keep a concentrated winding set, which avoids physical coil contact and can give lower mutual inductance, making it preferable for fault-tolerant drive applications. Both the proposed 24S-14P dual three-phase motor and conventional 12S-14P motor have been designed for a traction application. The comparative study shows that the proposed 24S-14P dual three-phase motor not only exhibits much lower space harmonic content and much lower iron losses but also has an improved torque capability and efficiency. Therefore, it is confirmed that the proposed 24S-14P dual three-phase system is a promising solution to the challenges of significant space harmonics for FSCW motor.

6 Acknowledgments

This work is funded by the INNOVATIVE doctoral programme. The INNOVATIVE programme is partially funded by the Marie Curie Initial Training Networks (ITN) action (project number 665468) and partially by the Institute for Aerospace Technology (IAT) at the University of Nottingham.

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