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Rotor Loss Reduction Using Segmented Inverter in Surface-Mounted Permanent Magnet Drive

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***Abstract*—In this paper, the influence of different switching modulation arrangements, i.e. current waveform modulation- and phase-shift, on the resultant current waveform of an electrical machine drive consisting of a two segment inter-leaved inverter feeding a surface-mounted permanent magnet (SPM) machine with two identical sets of three phase windings is investigated. The modulation- and phase-shift have been illustrated and the influence of the different modulation and frequency indices have been studied. Furthermore, the torque, and rotor eddy currents and core losses are calculated using FEA when either modulation-shifted or phase-shifted current waveforms are generated and fed to the machine. It is found that using modulation-shift can reduce the current harmonic substantially however the inverter requires two sets of input signals. On the other hand, although the current harmonic reduction is less than that of the modulation-shift, the phase-shift layout can be employed using one set of input signals with a signal delay.**

Keywords—Inter-leaved inverter, segmented inverter, SPM, surface-mounted, loss reduction, eddy current loss

I. INTRODUCTION

Surface–mounted permanent magnet (SPM) machines have been under research and development over the past decade due to their multiple applications, e.g. automotive and aerospace. Despite their advantages of high power density and efficiency, SPM drives have several rotor electromagnetic, mechanical and thermal challenges. One of the main challenges is the eddy current loss in the conductive rotor components, i.e. magnets and sleeve, due to unsynchronized time- and space-harmonics, which causes an efficiency reduction and temperature rise in the rotor [1].

Several methods have been proposed to reduce the rotor eddy current loss. These methods can be summarized as: 1) external inductance to smooth the current waveform [2], 2) closed-slot and slotless topologies to reduce stator space harmonics [3-4], 3) axial and radial segmentation of the PMs or axial segmentation of the sleeve as a solution for the eddy currents [5-6], 4) sleeve shaping (groove or gaps) to cut the eddy current path [7-8], 5) pulse amplitude modulation (PAM) to reduce the effective current ripple [9], 6) high conductive shielding of harmonic effect [10-11], and 7) large airgap to reduce the effect of space harmonics [12].

Inter-leaved or segmented inverters have been proposed to scale up the inverter system power ratings [13-14], reduce the AC output filters [15-16], reduce the DC bus capacitor [17-18] and reduce the current ripple [19-20]. The electrical drive of such a system consists of two inverters and an electrical machine with two identical stator winding sets. By default, since this concept reduces the current ripples, i.e. time harmonics, the induced eddy current loss in the rotor is expected to be reduced.

To illustrate the reduction of the current ripples, the authors of [19-20] suggested a 180° shift of the triangular carrier of the pulse width modulation (PWM) switching signal of one of the two inverters, Fig. 1. This leads to a 180° shift in the current ripple of this inverter and therefore when it feeds one set of the stator windings simultaneously with the other inverter feeding the other set, the resultant current waveform would effectively have reduced harmonics. However, this approach requires two sets of switching signals and therefore, a more powerful CPU is needed. Alternatively, the current ripples can also be reduced by phase-shifting one of the current waveforms. This can be achieved by either an inductive load placed between the inverter and the winding set or by a mean of signal delay. However, an inductive load can result in a reduction in the current amplitude. Similar to the modulation shift, when a shifted current waveform feeds one set of the stator winding simultaneously with the other inverter feeding the other set, a reduced harmonic content in the resultant current waveform is expected.

In this paper, the two modulation arrangements: modulation-shift and phase-shift have been illustrated and explained. Different frequency and amplitude indices have been used to define their influence on the investigated modulation arrangements. Furthermore, a comparison between the torque, and rotor and core losses of a two segment inter-leaved high-speed drive with different current arrangements, i.e. modulation-shift and phase-shift, has been conducted using 2D-FEA. The comparison concentrates on the influence of the current on the torque and torque ripple, and reductions in core and rotor losses.

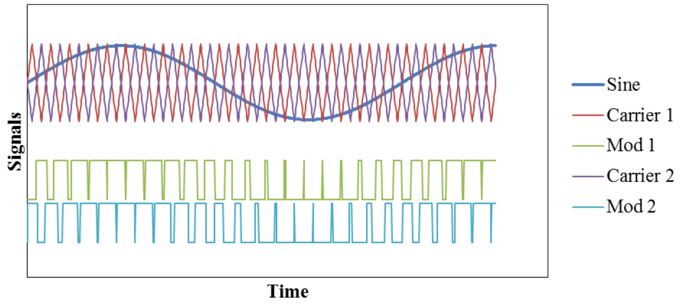

Fig. 1. Modulation-shift pattern.

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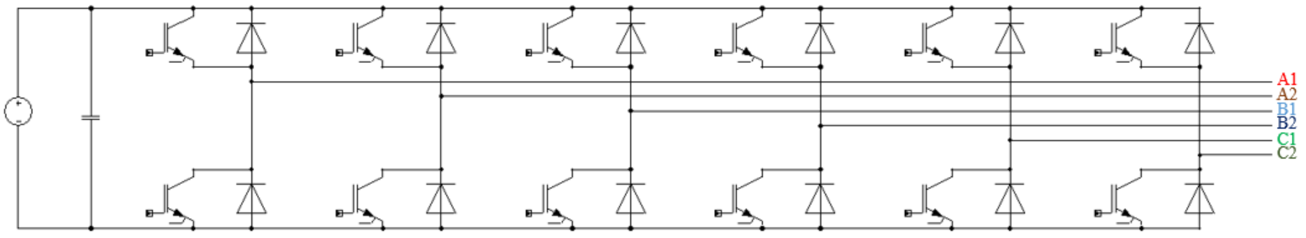
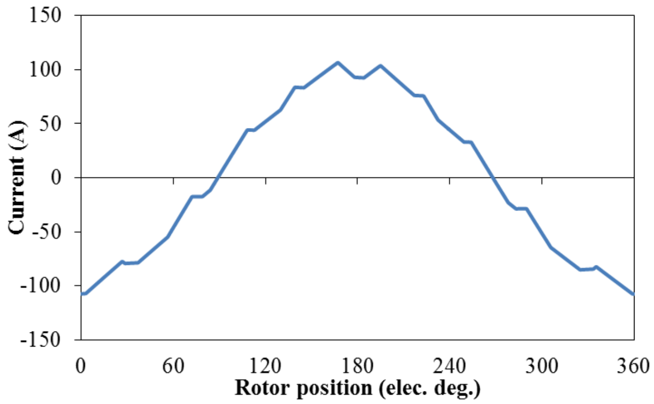


Fig. 2. Inter-leaved SPM inverter.

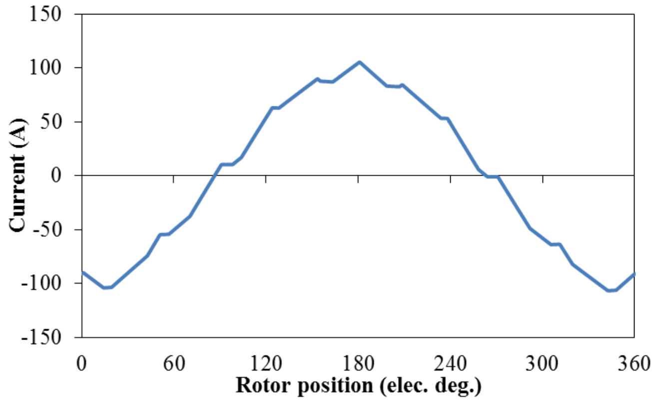
II. MODULATION- AND PHASE-SHIFT

A. Modulation-shift

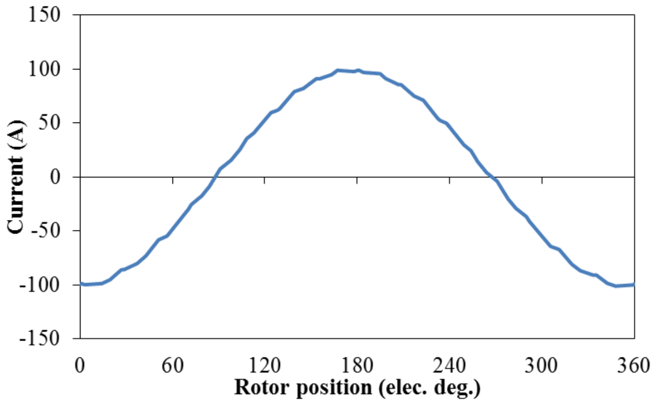
Fig. 3 illustrates the effect of modulation-shift on the resultant current waveform. The 180° shift of the triangular carrier results in a current waveform with most of the low order harmonics in the opposite direction to those in the original current waveform, Figs. 3 (d) and (e). Therefore, the resultant current waveform has a low harmonic content and therefore low total harmonic distortion (THD).



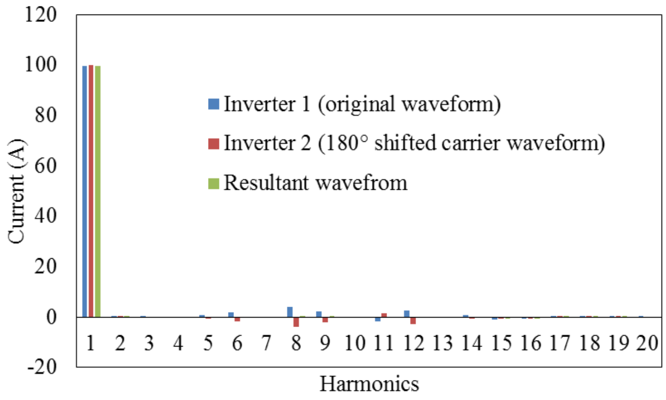
(a) Inverter 1 current (original waveform)



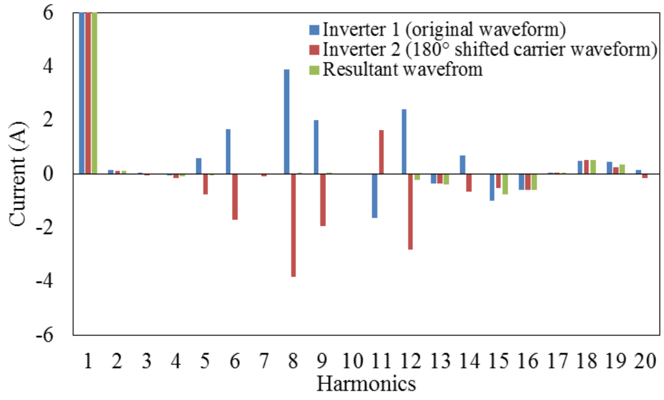
(b) Inverter 2 current (180° shifted carrier waveform)



(c) Resultant current waveform



(d) Current waveforms harmonics



(e) Current waveforms harmonics (lower scale)

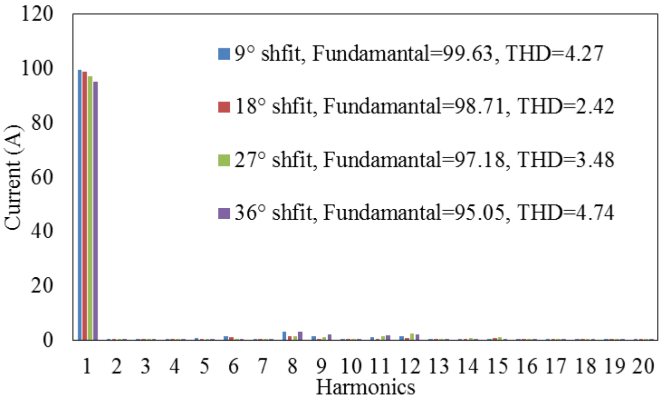
Fig. 3. Modulation-shift current wavefroms and harmonics.

B. *Phase-shift*

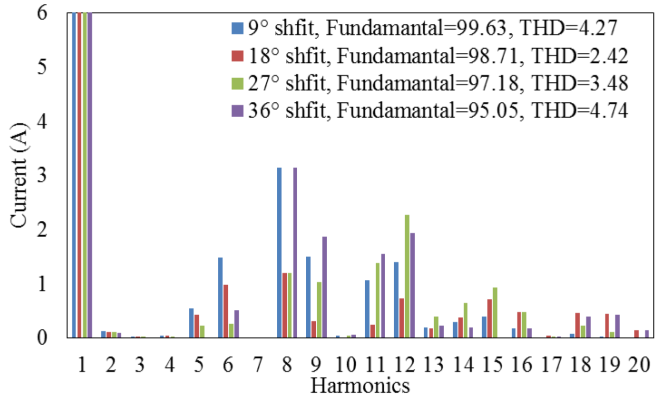
A phase shift between the two current waveforms leads to a resultant current with reduced harmonic content. To achieve the best THD reduction, the shifting electrical angle can be found by:

$$\alpha = \frac{1}{2}\left(\frac{360}{m_f}\right) \qquad (1)$$

where α is the shifting angle and m_f is the frequency modulation.

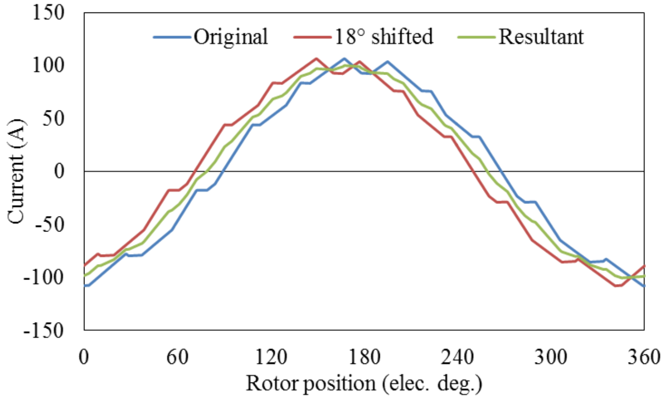


(a) Current waveforms harmonics



(b) Current waveforms harmonics (lower scale)

Fig. 4. Phase shift current wavefroms harmonics (9, 18, 27 and 36 degrees).



(a) 18 degree shifted current

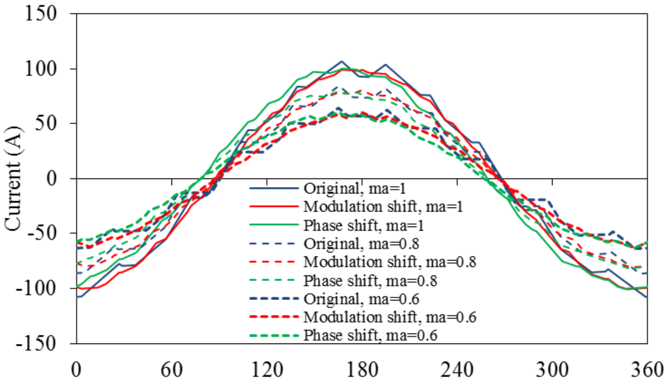
(b) 36 degree shifted current

Fig. 5. Current wavefroms with 18 and 36 degree shifted

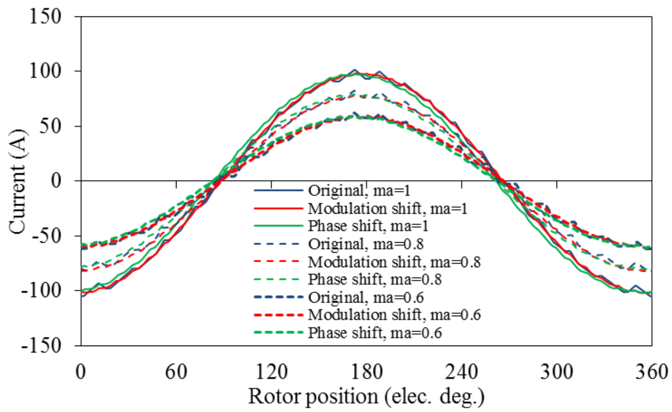
To illustrate this effect the harmonics generated in resultant current waveforms with shifts of 9°, 18°, 27° and 36are shown in, Fig. 4. It can be seen that the lowest THD is found with the 18° shift, as shown in Fig. 5, since the switching fluctuation in both the original and shifted waveforms occurs at the same instant. In addition, though the THD of the resultant current waveform reduces with shifting angle, due to the phase shift a reduction in the current fundamental component is observed.

C. *Amplitude and Frequancy Indices*

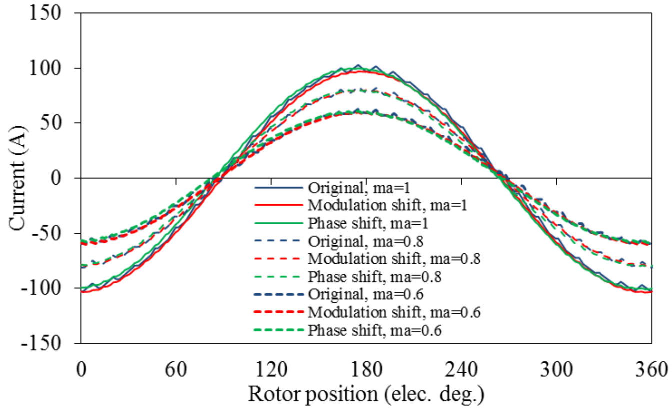
The effects of modulation- and phase-shift have been studied using frequency modulation indices of 10, 20 and 30 and amplitude modulation indices of 0.6, 0.8 and 1. Fig. 6 presents the current waveforms of the studied indices, and Tables I and II lists their fundamental and THD, respectively.



(a) Frequency modulation index=10



(b) Frequency modulation index=20



(c) Frequency modulation index=30

Fig. 6. Current wavefroms of diffenert frequency and amplitude indices.

TABLE I. Fundamental of Original, Modualtion- and Phase-shift Current Wavefroms.

	Original	**Modulation-shift**	**Phase-shift**
ma	*mf=10*		
1	99.94	99.88	98.71
0.8	79.46	79.47	78.50
0.6	59.65	59.62	58.93
ma	*mf=20*		
1	99.25	99.67	98.95
0.8	79.23	79.61	78.99
0.6	58.98	59.18	58.81
ma	*mf=30*		
1	100.78	100.51	100.65
0.8	79.89	79.94	79.78
0.6	59.28	59.52	59.20

TABLE II. THD of Original, Modualtion- and Phase-shift Current Wavefroms.

	Original	**Modulation-shift**	**Phase-shift**
ma	*mf=10*		
1	5.88	1.60	2.42
0.8	8.17	1.82	2.68
0.6	10.60	2.05	3.00
ma	*mf=20*		
1	2.85	0.80	0.91
0.8	3.99	0.92	1.02
0.6	5.22	1.11	1.24
ma	*mf=30*		
1	1.89	0.55	0.68
0.8	2.68	0.80	0.87
0.6	3.50	0.87	0.91

It can be seen that the fundamental of the modulation-shift current has changed slightly either to a higher or lower value than the original. This is due to the change in the harmonic locations around the peak of the current waveform. However, the phase-shift fundamental values have reduced by 1.2%, 0.3% and 0.13% in the frequency modulation indices of 10, 20 and 30, respectively. The reason is the resultant of two shifted current waveforms gives in a reduction in the peak, and the reduction increases with the increase of the shifting angle. Also, the THD is lower with modulation-shift compared to phase shift. However, at lower amplitude indices a smaller difference between the modulation- and phase-shift THD can be seen, especially at higher frequency indices.

III. Comparison of SPM Machine Performance with Phase and Modulation Shift

To evaluate the proposed methods, 2D-FEA model of the SPM machine has been analysed using a current waveform generated by PWM with frequency modulation index of 10 and amplitude modulation index of 1 has been used. Three cases have been compared; 1) both windings sets fed by the same waveform (original), 2) one winding set fed with the original waveform and the other with a phase-shifted current waveform (phase-shift), 3) one inverter fed with the original waveform and the other with a modulation-shifted current waveform (modulation-shift). Table III lists the resultant current waveform amplitude and total harmonic distortion (THD), average torque, torque ripple percentage, rotor eddy current loss and stator core loss of the three investigated cases. Fig. 7 presents the torque waveform of the three cases.

The average torque of both modulation- and phase-shift cases reduced slightly due to the reduction in the current amplitude. The torque ripple reduced by 60% and 44% in the modulation- and phase-shift, respectively. Moreover, the rotor loss reduced by 37% in the phase-shift and 38% in the modulation-shift, since the current waveform in both modulation and phase-shift is essentially sinusoidal, the effect of the current time harmonic has been reduced significantly and the rotor loss are produced by mainly the space harmonics. Finally, similar core loss is found in the three studied cases.

TABLE III. Normailized Performance of SPM Machine with Inter-leaved Inverter

Parameter	**Unit**	**Original**	**Phase-shift**	**Modulation-shift**
Current amplitude	A	1	0.987	0.999
Current THD	-	1	0.373	0.265
Average torque	Nm	1	0.981	0.992
Torque ripple	-	1	0.557	0.397
Rotor loss	W	1	0.627	0.618
Core loss	W	1	0.996	1.001

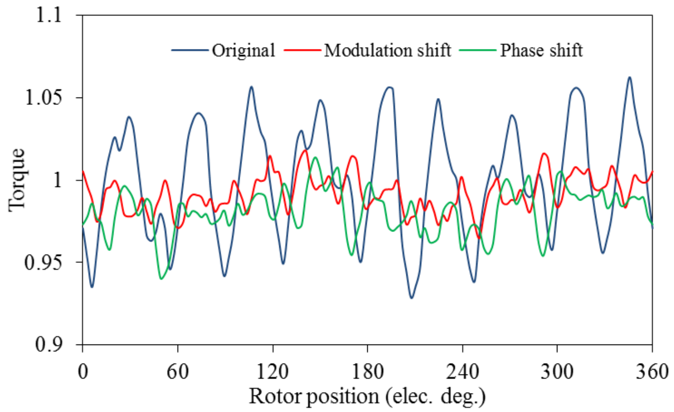


Fig. 7. Normailized electromagnetic torque wavefrom of the original, modulation-shift and phase-shift.

IV. CONCLUSION

This paper presents an inter-leaved inverter drive with two different current modulation arrangements, phase-shift and modulation-shift, designed to reduce the current ripples and therefore the rotor eddy current losses. From the investigation, it is found that using modulation-shift gives higher current waveform fundamental and lower THD, therefore, higher torque and lower rotor loss compared to using phase-shift. However, the difference between the two modulation methods is relatively small and both methods provide a substantial reduction in current THD and therefore rotor loss compared to the unmodulated waveform. Phase-shifting should therefore still be considered since it can be achieved through a simpler drive modification, inductive load or signal delay.

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