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Improved Modulation Methods of the Dual-inverter Fed Open-end Winding Three-phase Motor Drives with Equal DC-link Voltage

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Abstract*— *This paper investigates PWM method for the dual-inverter fed open end winding three-phase induction motor drives. This is aimed to improve the quality of the output voltage as well as to enhance the motor performance by solving the drawback of the PWM method. The proposed PWM method operates two inverters in different technique, i.e one inverter operates in square wave mode (slow switching) and one inverter in PWM mode (fast switching). Although the PWM method can improve the quality of the inverter output voltage over the two-level inverter output, the proposed PWM method causes an excessive ripple in both torque and stator current especially at the transient period. The drawback is solved by applying a new switching strategy that manage the inverter switches operate in turn between slow switching and fast switching in one circle of operation. The proposed method is verified via simulation. The result shows that the quality of output voltages improves for all modulation indices in comparison with two-level inverter. Furthermore, torque ripple is reduced, and current ripple are improved as the current waveform is enhanced to be more symmetrical.

Keywords*—*Dual-inverter fed, Modulation technique, Open-end winding, PWM.

I. Introduction

Electric vehicles offer many advantages compared with combustion cars, including environmentally friendly, digitally compatible where the parameters are very suitable to be controlled and monitored digitally and using a Microcontroller [1]. One challenge in the development of EV is the efficiency of the power supply which affects the speed and distance travelled. Various efforts to overcome this problem have been carried out, including combining various power supply sources, combining batteries with supercapacitors [2,3,4]. Another technique to increase the reliability of electric vehicles is to apply a dual power supply system / dual inverter [5,6]. Figure 1 shows the schematic circuit of dual inverter fed structure. In the dual-inverter system, the neutral point of the motor stator winding is opened which is known as open-end windings so that the motor can be supplied from both sides. The use of a dual-inverter system requires appropriate modulation techniques. Several studies have been carried out and mostly focused on improving the quality of the inverter output voltage (eliminating harmonics), and developing simpler modulation techniques [7,8]. This paper investigates the effect of the modulation strategy to the performance of dual-fed open-end winding Induction motor drives. The inverter output voltages, speed, torque, and stator currents are evaluated and compared for various PWM methods.

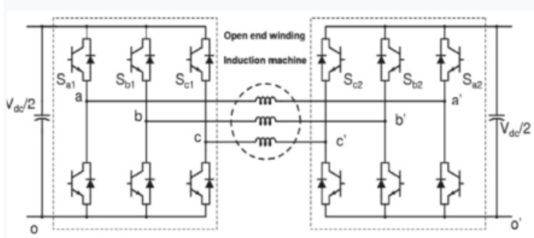

Fig. 1. Dual inverter fed open-end winding motor structure [9]

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II. METHODOLOGY

A. Review of PWM Methods for two level -inverter (Heading 2)

The well-known PWM methods for 3-phase inverters, namely Sinusoidal PWM (Sin-PWM), and Space Vector PWM (SVPWM). Sin-PWM generates pulses by comparing sinusoidal reference with high frequency carrier signal. The carrier signal can be in form of triangular or saw-tooth signal. The value of pulses is determined by a simple logic. If the reference is higher than the carrier, the pulses is high (1), in contrast, if the reference lower than the carrier the value of pulses is low (0). Meanwhile, SVPWM generates pulses by employing a certain procedure based on the available space vector voltages in the α-β two-dimensional plane as shown in Fig. 2. The SVPWM algorithm can be summarized as below.

(1) Dividing the plan into six sectors
(2) Applying 3 nearest vectors to the reference for each sector that consists of two active vectors and one zero vector
(3) Calculating time application of the applied vectors
(4) Determining the switching pattern for each sector.

Despite of the long-step procedures, SVPWM is beneficial due to the method can generate higher voltage output compared with the Sin-PWM by factor 1.15 [10].

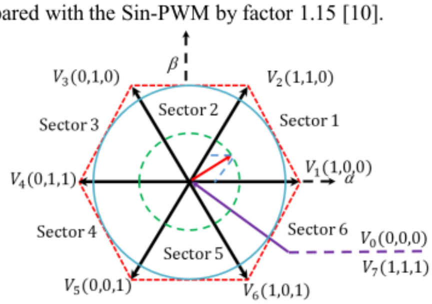

Fig. 2. Mapping of Voltage Space Vector of two-level 3 phase inverter in a-b plane [11]

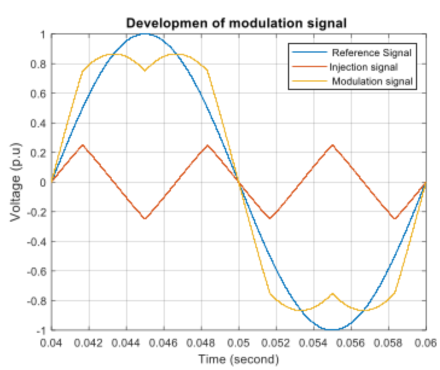

Fig. 3. The way to generate modulation signal in CB-SVPWM

Lately, equivalent carrier Based Space Vector PWM (CB-SVPWM) is introduced. CB-SVPWM is the method that based on the comparison of the modulation signal and the carrier signal to generate pulses. The modulation signal is obtained by injecting the sinusoidal signal with the sum of number sinusoidal signals with different magnitude and frequency. The PWM generated by the equivalent CB-SVPWM method is the same with the Space Vector method hence the performance is also the same. Figure 3 shows the way to obtain the modulation signal, while Figure 4 shows the comparison the modulation signal and carrier signal at frequency fundamental of 50 Hz.

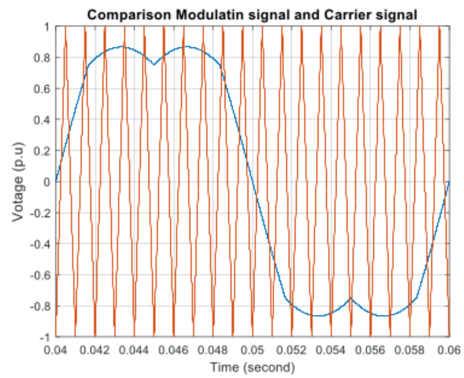

Fig. 4. Comparison of modulation signal and the carrier signal

In this paper the equivalent carrier-based SV-PWM method is applied for the dual inverter fed open-end winding 3-phase motor. The proposed PWM method is explained in the following section.

B. PWM method of dual-inverter fed Open- end Winding motor drives

The development of PWM methods for the dual-inverter fed is carried out by dividing the voltage references for the two inverters hence reduce complexity. The proposed PWM method works according of the modulation index (M). Modulation index is defined as the ratio of the fundamental component amplitude of the inverter output voltage to one-half of the DC-link voltage. In variable speed drive, since the v/f = constant is applied; modulation index is also related with frequency of the inverter output. Here, at M equals to 1, the frequency of the output voltage is set at 50 Hz. Maximum modulation index for the Space Vector PWM is 1.15 or relates with 57.5 Hz.

The proposed PWM method for the dual-inverter fed with equal DC-link voltage can be explained as follows. At the low modulation indices ($0 < M \leq 0.575$) only one inverter is operated using CB-SVPWM while the second inverter is clamped at zero states (000), to bring the system is back to single-sided supply configuration. At higher modulation indices ($0.575 < M \leq 1.15$), the two inverters are operated. The first inverter works at fundamental frequency to produce the square waveform in the output and the second inverter is modulated in high frequency i.e 1000 Hz. The modulation signals for the second inverter are achieved by subtracting the sinusoidal waveforms with the square waveform which is generated by the first inverter as shown in Fig. 5. Subsequently the PWM pulses are generated by using carrier-based method, i.e comparing the modulation signal

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with high frequency triangular signal. As already mentioned, in CB-PWM method, the generated pulses are governed by a simple rule. If carrier signal is higher than the modulation signal, then the pulses is high (1) and otherwise the pulses is low (0).

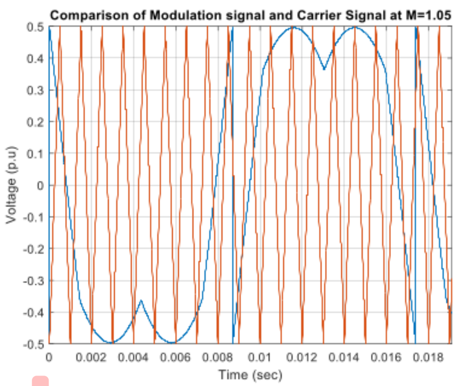

Fig. 5. Comparison of modulation signal and the carrier signal

Fig. 5 shows the phase a modulation signal along with reference signal and normalized of the phase a voltage output of inverter-1 that operates at fundamental frequency. Fig. 6 shows the PWM signals of the first inverter for the upper switches and the lower switches at M=1.05 while PWM signals of the second inverter for phase an upper and lower switches are shown in Fig. 7.

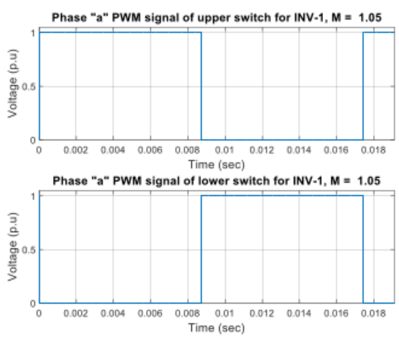

Fig. 6. Phase 'a' PWM signal of dual inverter fed structure for inverter -1

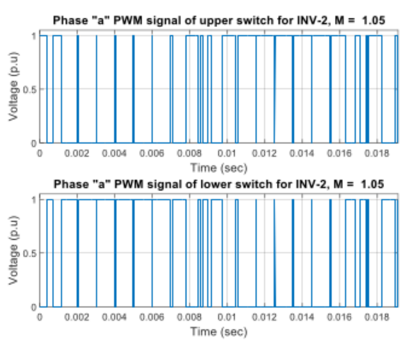

Fig. 7. Phase 'a' PWM signal of dual inverter fed structure for inverter -2

III. Result And Discussion

The proposed PWM methods are verified using MATLAB/Simulink. The two inverters utilize 6 MOSFET respectively. The inverters are modeled using Sim's cape and the PWM pulses are generated using Simulink. High frequency inverter is operated at 1 kHz. Induction motor parameters are resumed at Table 1.

TABLE I. Induction Motor Parameter

Motor Parameter	Value
No. of pair pole (P)	2
Voltage input	220 V
Frequency input (f)	60 Hz
Stator Resistance, Rs	10 Ω
Rotor Resistance, Rr	6,3 Ω
Stator Inductance, Ls	0.04 H
Rotor Inductance, Lr	0.04 H
Mutual Inductance, Lm	0.42 H
Motor Inertia, (J)	0.01

A. Inverter Output Voltages

The developed PWM methods were tested for various modulation indices, Fig. 8 and Fig. 9 show the voltage output at M = 1.0 and M=0.5 and the harmonic spectrum respectively. At M=1.0, the voltage consists of 9 level voltage while at M = 0.5 the voltage output consists of 5 level voltage. At M = 0.5, only one inerter is operated since the system revert into two-level inverter.

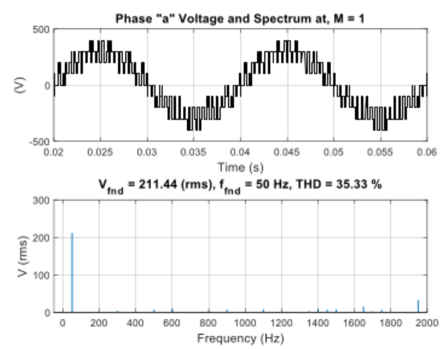

Fig. 8. Inverter phase 'a' output voltage at M = 1.0

Simulation was repeated for various modulation indices (M) from 0.05 to 1.15 with 0.05 increment steps. The magnitude of the fundamental output and the value THD is resumed and presented in Table 2 and Fig.10. Table 2 and Fig. 10 clearly reveal that the dual inverter fed structure generates a significant improvement of the output voltage for all modulation indices that indicates by the lower value of THD while the value of fundamental output is relatively the same.

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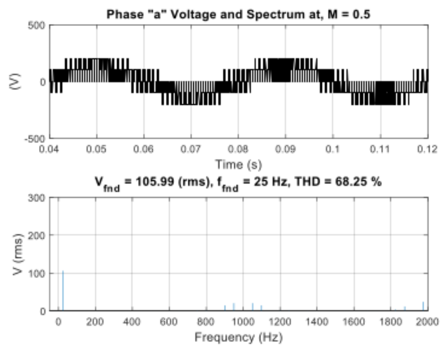

Fig. 9. Inverter phase 'a' output voltage at $M = 0.5$

TABLE II. THD COMPARISON OF TWO-LEVEL AND DUAL-TWO LEVEL INVERTER

No	m	Two-Level inverter		Dual Two-level	
		Fund	THD_v (%)	Fund	THD_v (%)
1	1,15	243,37	52,39	243,05	27,48
2	1,10	233,29	57,80	233	39,83
3	1,05	222,56	62,95	212	32,91
4	1,00	211,91	68,32	211,45	35,32
5	0,95	200,97	73,98	200,93	37,17
6	0,9	190	79,13	190,86	39,09
7	0,85	180,06	85,03	180,28	40,39
8	0,8	169,45	91,13	168,55	42,34
9	0,75	158,7	97,86	159,7	42,79
10	0,7	148,31	104,4	148,22	44,24
11	0,65	137,64	111,80	137,22	45,51
12	0,6	127,11	119,8	127,24	48,87
13	0,55	116,54	128,8	116,39	57,8
14	0,5	105,9	138,7	105,84	68,33
15	0,45	95,36	149,9	95,22	79,38
16	0,4	84,74	162,7	84,71	91,18
17	0,35	74,14	178	74,06	104,7
18	0,3	63,51	196,4	63,477	120,1
19	0,25	52,99	219,2	52,94	138,8
20	0,2	42,44	249,5	42,35	162,9
21	0,15	31,824	292,8	31,729	196,5

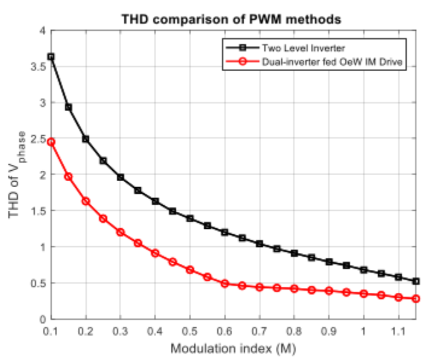

Fig. 10. THD comparison of two-level inverter and dual two-level inverter

B. Motor Performance

Further, the dual-inverter fed an open-end 3-phase induction motor is analyzed. The motor performance in term of speed, torque and stator current is presented. Fig. 11 shows motor speed – torque in both acceleration and deceleration mode. Motor speed was changed from 500 rpm to 1300 rpm at t = 0.5 second. At t =1,0 the motor speed is reduced to 700 rpm. At t = 1.5 second, the load N = 5 N-m is applied that further slightly reduce the speed of motor. While stator current is presented in Fig. 12.

It is clearly shown in Fig. 11 that the expected motor speed is achieved in least tan 0.2 second. Transition among speed is successfully obtained without any excessive overshoot. It is however the motor torque is highly fluctuated during the transient period of the speed especially at the acceleration period from 500 rpm to 1300 rpm.

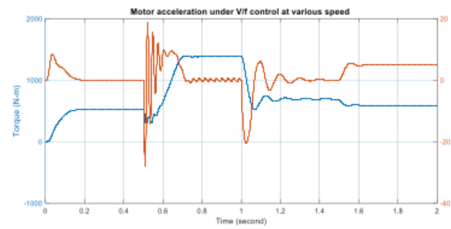

Fig. 11. Torsi-torque response under open loop v/f control with the proposed PWM method

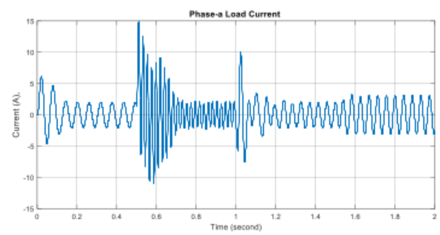

Fig. 12. Phase 'a' stator current of the induction motor driven by the proposed PWM

Furthermore, in line with motor torque, the stator current also shows an erratic fluctuation during acceleration period. Further investigation reveals that the applied PWM method tends to make motor produce an asymmetrical current and highly current ripple particularly at M > 0.575 when both inverters operate. The asymmetrical current occurred because at M > 0.575 the two-inverter applied with different PWM method. i.e one inverter operates in square waveform and inverter 2 operates in PWM mode.

C. Improved PWM method

To solve the problem of an asymmetrical voltage and current, a new PWM method is proposed i.e by alternating the switching between two inverters. The PWM method is realized by placing the modulation signal and the carrier signal in a such way so that the inverter's PWM signal of each cycle of operation consist of combination of slow switching and fast switching pulses as shown in Fig. 14. While Fig. 13 shows the comparison of the modulation signal and the carrier signal for inverter-1 and inverter-2.

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The motor performance driven by the new switching strategy is shown in Fig. 15 and 16.

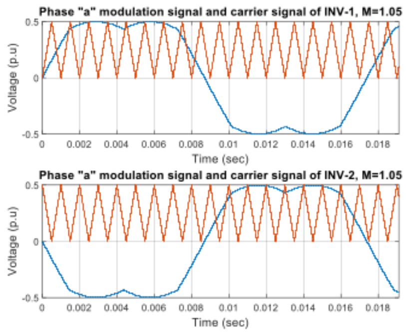

Fig. 13. Proposed Alternate switching PWM method for the dual inverter fed OeW motor drives

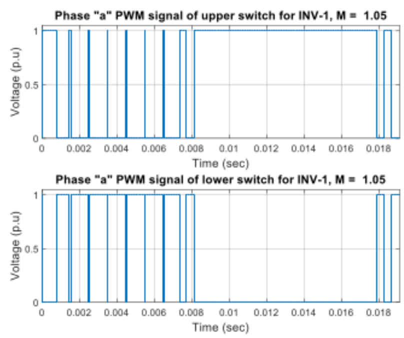

Fig. 14. Improved switching pulses for the dual inverter fed OeW motor drives

Fig. 15 shows the torque-speed relationship at various motor speeds with alternate switching PWM method. It is clearly shown in Fig. 15 that the fluctuation of the torque during transient period is significantly reduced as well as the torque ripple during state also improved.

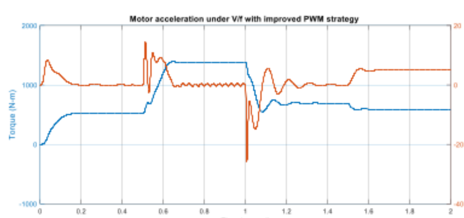

Fig. 15. Torsi-torque response under open loop v/f control with the new PWM method

Furthermore, Fig. 16 depicts that the current ripple is reduced during acceleration and the whole current waveform is improved hence it becomes more symmetrical as the value between the positive side and the negative side is now more proportional in value.

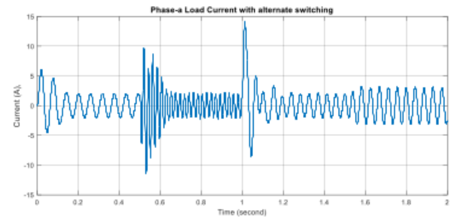

Fig. 16. Phase 'a' stator current of the induction motor with new switching strategy of PWM method.

IV. Conclusion

Carrier based Space Vector PWM methods for the dual inverter fed open-end winding induction motor drives have been discussed in this paper. The proposed PWM method operates one inverter in square wave mode and one inverter in PWM mode. A new switching strategy is introduced to solve the drawback of the proposed PWM method by alternating the switching pulses for everyone cycles of operation. As a result, the torque and current ripple is successfully reduced, and the current waveform is improved to be more symmetrical.

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