Two Different Carrier Phase Shifted Space Vector PWM Techniques for Pole Phase Modulation based 9-Phase Induction Motor Drive

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Abstract

The pole phase-modulated induction motor (PPMIM) drives fulfils all significant requirements of high power traction applications, like extended speed-torque capabilities, higher fault tolerance and high efficiency. In the low pole high phase mode, PPMIM drive offers the high speeds for steady run application but in this mode, drive suffers from the lower DC-link utilization. In high pole low phase mode, the drive offers high torque for cruising and faster acceleration, however, the drive suffers from the higher torque pulsations. In this paper, these two limitations of 9-phase PPMIM drives are addressed by proposing a dual inverter-based multilevel inverter (MLI), where the drive is modulated with two different carrier phase shifted space vector pulse width modulation (SVPWM) schemes. For achieving the 3-level voltage across each phase the proposed inverter requires 4 DC source and 36 switches. Firstly, the DC link utilization of the proposed MLI fed 9-phase PPMIM drive is improved by 15.4%, where the drive is modulated by using 3-phase carrier-based SVPWM along with phase grouping concepts. In the high pole low phase mode, two different carrier phase shifted PWMs (CPS-PWM) are proposed for feeding the effective phase windings with multilevel voltage, which results in better torque ripple profile of PPMIM drive. In CPS-PWM1, both level shifted and phase shifted carrier PWM concepts are effectively used for modulating the proposed MLI configuration. Whereas in CPS-PWM2, phase shifted carrier PWM concept is used. The proposed MLI fed PPMIM drive with different PWMs are validated by using the Ansys Maxwell 2D as well as an experimental prototype.

1 Introduction

In the present situation, high power applications like traction, ship propulsion, electric vehicles, aircraft, etc., the fault-tolerant capability and high power handling with reduced power per phase are the two key constraints. In general, to meet these constraints the traditional three-phase machines have to be over-sized and extra circuitry is required, which enforces the interest towards the multiphase machines [1]. The machine with a higher number of phases will enhance the efficiency, spatial harmonic profile, handling of high power with reduced voltage ratings of the switches [1]-[5]. The multiphase induction motors (MIM) are fed with power electronic inverters for achieving the variable speed and torque, which gives freedom to use any number of phases other than 3 phases (same as utility grid). Many pole phase modulation (PPM) based 9-phase, 15-phase, 45-phase induction motor (IM) drives are presented with a 2-speed (1:3 ratio), 3-speed (1:3:5 speed ratio), 5-speed (1:3:5:9:15 speed ratio) respectively, for getting wider range of torque-speed response [3], [6]-[10]. The 9-phase PPM based IM drive will operate in 9-phase 4-pole (9PH-4PO) mode and (3PH-12PO) mode, where drive delivers high torque at low speed in high pole mode and low torque at high speed in low pole mode [7]. However, in high pole the reduced phase order of PPM based IM drive will increase the magnitude of spatial harmonics, magnetizing current and torque ripple magnitude [11]-[12].
For improving the performance of the PPM based 9-phase IM drives the multilevel inverter configurations has to be adopted, where phase windings of the machine are excited with multilevel voltage with minimized time harmonics. The conventional multilevel inverters (MLI) are neutral point clamped (NPC), flying capacitor (FC) and cascaded H-bridge (CHB) [13]. In these MLIs the device count is directly proportional to the phase order, like a higher number of diodes in NPC MLI, capacitors in NPC and FC MLIs, isolated DC sources in CHB MLI. The dual inverter (DLI) concept is proposed for open-end winding (OEW) IM in 1993 for high power applications with lesser number devices [14]. In this DLI configuration, the phase windings are excited with traditional 2-switch inverter legs (2-level inverters) from both ends. Here, the effective voltage is 3-level voltage which is the sum of voltages generated by two 2-level inverters. Based on this DLI concept many MLI configurations has discussed for MIM drives [6]-[7],[15]-[16], where the number of levels, as well as time harmonics in-phase voltage, are improved as compared to 2-level inverter voltage. A 3-level and 4-level MLI configurations for PPMIM drives are discussed by using the DLI concept, where 4 DC sources with symmetrical and asymmetrical magnitudes [7],[15]. For OEW IMs another type

of DLI configurations are presented with a single DC source where the isolation for minimizing the circulating current is presented inside the machine [16].

The carrier phase-shifted PWM (CPS-PWM) modulated CHB and modular MLIs is another type of MLIs where the output voltage has a higher number of levels and harmonics at the lower order multiples of the carrier frequency are cancelled each other. With this CPS PWM concept, many MLI configurations are proposed for MIM drives in [17]-[19]. The MLI configurations present in [7], [15] has modulated with CPS-PWMs to get the better performance of PPM based MIM drive, but the possibilities of carrier phase-shifted PWMs are not explored in these papers. In low torque and high-speed mode, the enhancement in linear modulation range (LMR) is limited due to the higher of phases [18]-[20]. The LMR of the 9-phase IM drive with 9-phase Space vector pulse width modulation (SVPWM) is 1.54% only over sine PWM (SPWM) [20]. Similar to the 3-phase SVPWM for getting 15.4% improvement in LMR, the 9-phase IM drive has to be modulated with 3-phase SVPWM. For this, the 9-phase system has to be rearranged in such a way that the zero sequence or circulating currents should not flow in the phase windings.

This paper mainly focuses on enhancing the performance of drives in terms of following,

1) Multilevel voltage generation with improved time harmonics by using carrier phase-shifted PWMs in 3PH-12PO mode for getting better torque ripple.
2) Enhancement in LMR in 9PH-4PO mode.

2. Prosed MLI fed 9-phase PPMIM Drive

The Proposed MLI configuration by using DLI concept is presented in Fig. 1. This MLI is implemented with the help of 18 two-switch inverter legs (six 3-phase inverters), 4 DC sources and 2 four-quadrant switches (FQS). The DC source magnitude of three-phase IM drive is V_{dc}, whereas in the proposed 9-phase PPM based IM drive the required magnitude of DC link voltage is $V_{dc}/6$. The blocking voltage ratings of all switches will $V_{dc}/6$. In DLI concept each end of OEW of phase-*a* is excited with one 2-level inverter. Here each 2-level inverter will generate $+V_{dc}/6$ and 0; thereby an effective number of level in phase-a voltage are $+V_{dc}/6$, $-V_{dc}/6$ and 0, the possible switching states of phase-*a* are shown in Table.1.

The Proposed MLI fed 9-phase PPM based IM drive will give the wider range of speed-torque characteristics by controlling the machine at different pole phase operations, i.e., 9PH-4PO and 3PH-12PO modes with a rated synchronous speed of 1500 rpm and 500 rpm respectively. The detailed

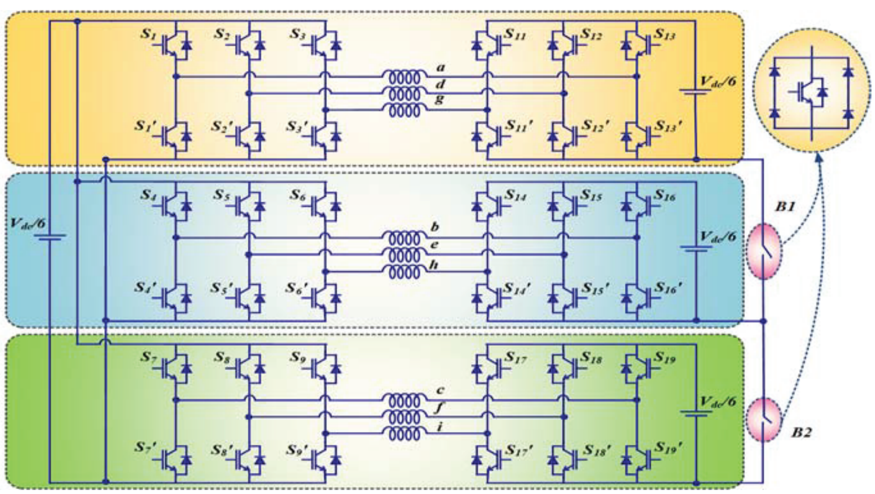


Fig. 1. Proposed 3-level inverter fed 9-phase PPM based IM Drive.

Table.1: Switching states and control logic for phase-*a*

Switches	Possible voltage levels				CPS-PWM1		CPS-PWM2	
	$+V_{dc}/6$	0	0	$-V_{dc}/6$	9PH-4PO	3PH-12PO	9PH-4PO	3PH-12PO
S_1	1	1	0	0	Ref> C1	Ref> 0^0 C1	Ref> 0^0 C1	Ref> 0^0 C1
S_1"	0	0	1	1	S_1!	S_1!	S_1!	S_1!
S_{11}	0	1	0	1	Ref< C2	Ref< 0^0 C2	Ref< 180^0 C2	Ref< 180^0 C2
S_{11}"	1	0	1	0	S_{11}!	S_{11}!	S_{11}!	S_{11}!

S1! = S1 is complementary to S1" and S11!= S11 is complementary to S11", C1, C2 means carrier-1 and carrier-2 waves, Ref= Reference waves

Table.2: Regrouping details and excitation details of the 9 phase windings of 9-phase PPMIM drive

Pole Phase Operation	Group-1	Group-2	Group-3
9PH-4PO mode	a (0^0), d (120^0), g (240^0)	b (40^0), e (160^0), h (280^0)	c (80^0), f (200^0), i (320^0)
3PH-12PO mode	a (0^0), d (0^0), g (0^0)	b (120^0), e (120^0), h (240^0)	c (0^0), f (120^0), i (240^0)

description on the winding details, slot number, excitation details, and phase grouping concepts are presented in the papers [7], [15]. In this paper presents the two different carrier phase-shifted PWMs for improving the performance of 9-phase PPM based IM drives. The two CPS-PWMs are,

i) CPS-PWM1: the combination of level shifted a phase-shifted PWM (9PH-4PO mode: level-shifted PWM, 3PH-12PO mode: a combination of level shifted and phase-shifted PWM)

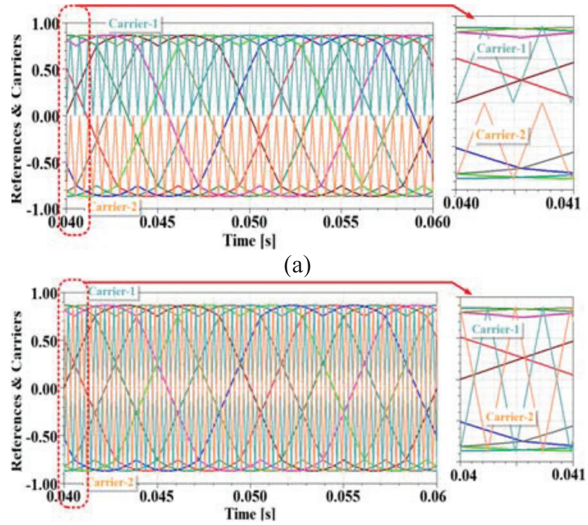
ii) CPS-PWM2: Phase shifted PWM (in both 9PH-4PO and 3PH-12PO modes phase-shifted PWM).

2.1. 9PH-4PO Mode

In 9PH-4PO mode, the machine phase windings are displaced by 40^0 with each other. With the 9-phase SVPWM, the LMR of the 9-phase drive is improved by 1.54% as compared to the SPWM [19]. This limitation on the enhancement in linear modulation range (LMR) is addressed by phase grouping concept, where the 9-phase windings are re-grouped into 3 sets of 3-phase windings, as presented in Table.2. These 3 phase groups are displaced by 40^0, where each 3-phase group has three 120^0 phase displaced windings. Each three-phase group is modulated with 3-phase carrier-based space vector PWM, which results in improvement of LMR by 15.4% over sine PWM. However, this carrier-based SVPWM implementation in the 9-phase system will cause for the flow of circulating currents due to the existence of zero sequence voltages in-phase voltage, which is denied by opening the four-quadrant switches (FQS) B1 and B2). The references and carrier for 9PH-4PO mode for CPS-PWM1 and CPS-PWM2 are presented in Fig. 2 (a) and (b) respectively. The control logic for generating the multilevel voltage in 9PH-4PO with both CPS-PWMs is presented in Table.1.

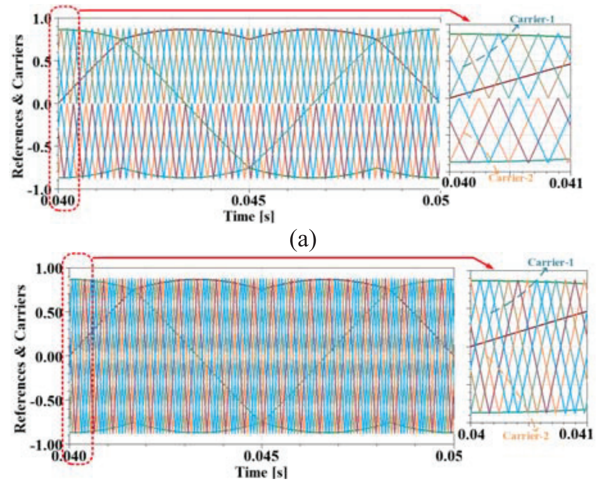
2.2. 3PH-12PO Mode

In 3PH-12PO mode, due to the reduced number of phases the magnitude of space harmonics increases in the airgap MMF. In this mode, the higher magnitude of space harmonics and the interaction of two opposite rotating airgap fields having the same pole number will result in higher torque ripple. For improving this, multilevel inverter schemes are proposed for the PPM based IM drives [15]-[19], where the time harmonics in the phase voltage are reduced. In this 3PH-12PO mode, for getting 3-phase rotating magnetic field the phase windings in each group has to be supplied with same fundamental voltage, since the windings *a, d, g* in group-1; *b, e, h* in group-2 and *c, f, i* in group-3 are electrically in phase, as shown in Table. 2. The effective phases in 3PH-12PO mode are group-1: Phase-R, group-2: Phase-Y, group-3: Phase-B. For achieving the multilevel voltage across each effective phase, the carrier of the inverter legs connected to the *a, d, g* windings in group-1 is modulated with the proposed CPS-PWMs. The CPS-PWM1 is the combination of level shifted and carrier phase-shifted PWMs, whereas the CPS-PWM2 is only phase-shifted PWM. Carriers and reference waves associated with CPS-PWM1 are presented in Fig. 3(a), where the carrier-1 and carrier-2 are level shifted for generating a 3-level voltage across phase-*a* but the other 4 carriers are phase-shifted by an angle of $360^0/3 = 120^0$ with a reference of carrier-1 and carrier-2 respectively. The CPS-PWM1 will increase the number of levels in effective voltage of Phase-R (sum of phase-*a*, phase-*d,* and phase-*g*) to 15 levels, where the carriers are displaced by 120^0. Similarly, the carriers and reference waves for CPS-PWM2 and the effective voltage of Phase-R are shown in Fig. 3(b) respectively. In CPS-PWM2 the 6 carriers associated with inverter legs of each group are displaced by an angle of $360^0/6$, which helps to generate the 9-level voltage across the Phase-R. Because of the proposed CPS-PWMs, the harmonics present at the lower order multiples of carrier frequency (like harmonics at 2kHz, 4kHz) are shifted by *x* times *of* switching frequency (where the *x*=number of phase-shifted carriers). This reduction in harmonics in the effective phase voltage, as well as multilevel



(a)
(b)

Fig.2. References and carrier for 9PH-4PO mode; a) CPS-PWM1 b) CPS-PWM2.



(a)
(b)

Fig.3. References and carrier for 3PH-12PO mode; a) CPS-PWM1 b) CPS-PWM2.

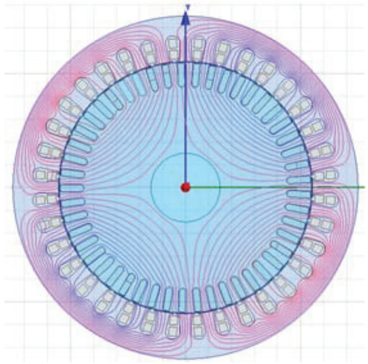


Fig. 4. Flux line distribution for 9PH-4PO mode.

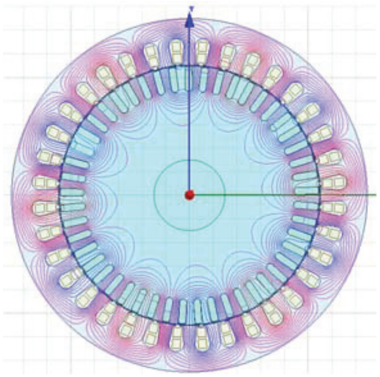


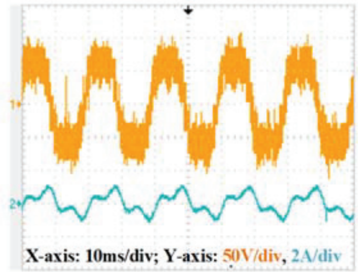
Fig. 5. Flux line distribution for 3PH-12PO mode.

voltage, will help for improving the performance of PPM based 9-phase IM drive

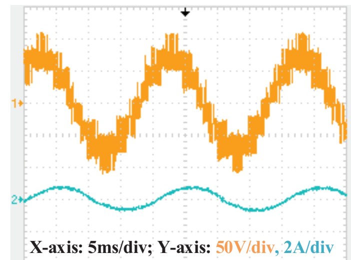
3. Results and Discussion

The 9-phase PPMIM drive is designed in Ansys Maxwell with a power rating of 5hp, 36/49 stator/rotor slots. This design is modelled with respect to the equations given in the literature [6], which helps in avoiding the crawling and magnetic locking effects. The validation of the proposed inverter fed 5hp 9-phase IM drive is also done by using the experimental prototype. Design details of the machine, as well as the inverter, are presented in the appendix. The proposed inverter configuration is realized by the 4 DC sources, six 3-phase inverter modules (36 power switches) and 2 four-quadrant switches. The 3-phase inverters are fabricated by using the 2 switch SEMIKRON inverter modules (SKM100GB128D) and respective gate driver circuits (M57962L). The proposed inverter fed 9-phase IM drive is controlled by generating the switching pulses with FPGA SPARTAN-6 board. The flux line distribution of the 9-phase PPMIM drive in both 9PH-4PO mode and 3PH-12PO mode are presented in Fig.4 and Fig.5 respectively.

Because of the 3rd harmonic injected SVPWM (carrier-based 3-phase SVPWM) without phase grouping concepts will cause for the flow of circulating currents in phase windings due to the presence of zero-sequence voltages in phase windings, as shown in the Fig. 6(a). The presence of lower order harmonics in phase voltage and currents will reduce the lifetime of the machine. To deny the circulating currents, the FQSs B1 and B2 are present in the proposed inverter circuit is turned OFF, which isolates the neutrals of three-phase groups, thereby the lower order harmonics in the phase windings has eliminated as shown in Fig. 6(b).

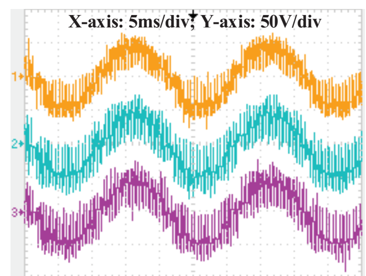


(a)

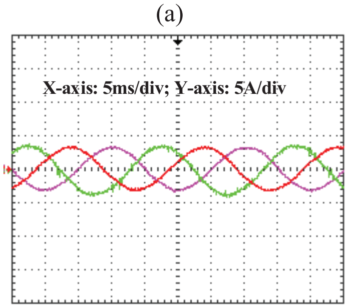


(b)

Fig. 6. Experimental voltage and current waveforms for 9PH-4PO mode; (a) without isolated neutrals, (b) with isolated neutrals.



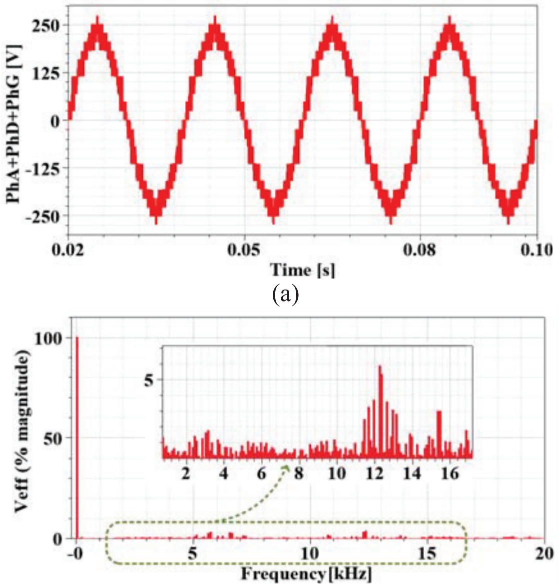
(a)



(b)

Fig. 7. Experimental voltage and current waveforms for 3PH-12PO mode with CPS-PWM1; (a) *a,d,g* winding voltages of phase-R, (b) Phase currents

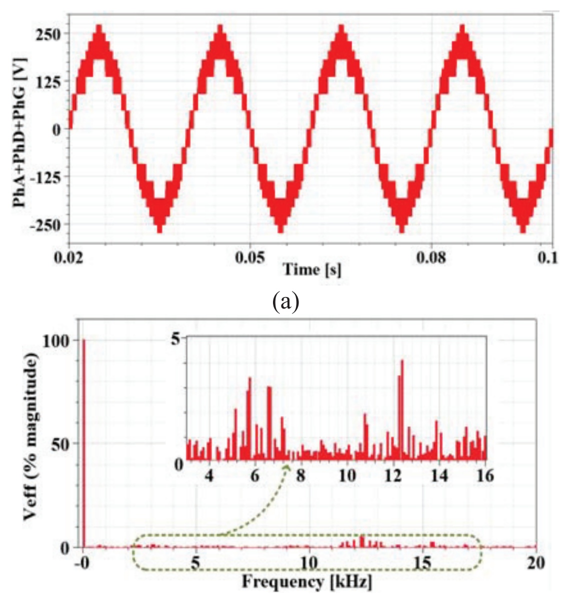
In 3-PH 12-PO mode, each effective phase is a combination of 3 IVPC windings which are getting the same fundamental voltages. With this advantage, the inverter legs feeding these 3 IVPCs are modulated with phase shifted carriers, i.e., with CPS-PWM1 and CPS-PWM2. The experimental voltages and



(a)

(b)

Fig. 8. FEM results for 3PH-12PO mode for CPS-PWM1, (a) effective phase voltage of Phase-R, (b) Harmonic spectrum of the effective phase voltage of Phase-R.

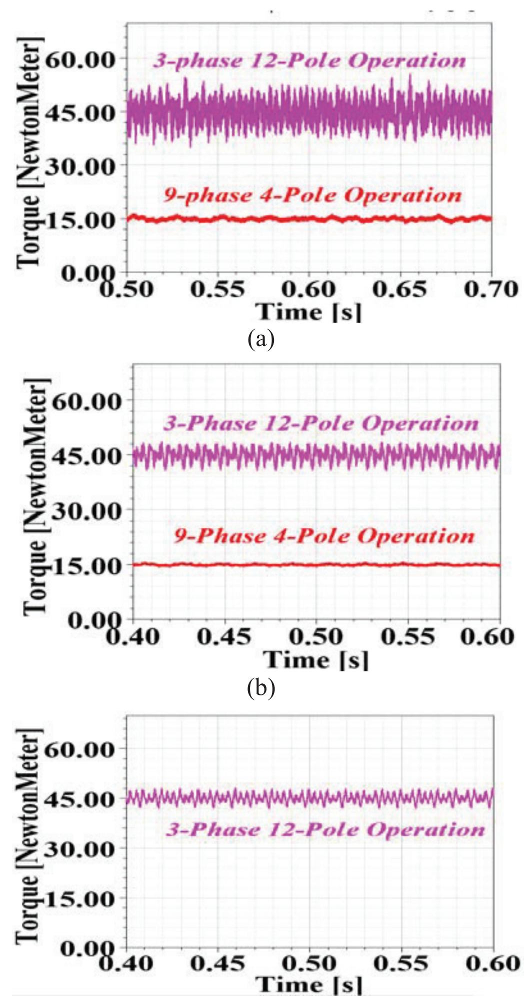


(a)

(b)

Fig. 9. FEM results for 3PH-12PO mode for CPS-PWM2, (a) effective phase voltage of Phase-R, (b) Harmonic spectrum of the effective phase voltage of Phase-R.

currents of the IVPC windings associated with phase-R with the CPS-PWM1, are presented in Fig. 7(a) and 7(b) respectively. The sum of these 3 IVPC winding voltages is equal to the effective phase voltage of the phase-R which is shown in Fig. 8(a) and the respective harmonic spectrum of Phase-R voltage is shown in the Fig. 8(b). Similarly, with the CPS-PWM2, effective phase voltage of the phase-R (the effective sum of the 3 IVPC winding voltages) as shown in Fig. 9(a) and the respective harmonic spectrum of Phase-R



(a)

(b)

(c)

Fig. 9. Torque response of the 9-phase PPMIM drive with, (a) 2-level voltage, (b) 3-level voltage, (c) with CPS-PWM1

voltage is shown in the Fig. 9(b). From the Fig.8 and 9, it is identified that the CPS-PWM1 and CPS-PWM2 excites the effective phase windings (R, Y and B) with the multilevel voltage, i.e., 15 and 9-level voltage respectively. From these figures, it is observed that the switching harmonics in effective phase voltage are shifted by 3 times with CPS-PWM1 and 6 times with CPS-PWM2. This reduction in harmonics in the effective phase voltage will help for improving the performance of PPM based 9-phase IM drive. The torque response of the proposed MLI fed 9-phase PPMIM drive is presented in Fig. 10 (a), (b) and (c) respectively. From this figure it is observed with CPS-PWMs the torque ripple percentage is significantly coming down as compared to 2-level and 3-level voltage.

4 Conclusion

In this work a DLI based MLI fed 9-phase PPMIM drive is presented. The proposed PPMIM drive is modulated with different carrier phase shifted PWMs, i.e., both level shifted and phase shifted PWMs are effectively used. With these proposed CPS-PWMs and phase grouping concepts, the limitations of the PPMIM drives like LMR in 9PH-4PO mode and torque ripple improvement in 3PH-12PO mode are addressed. The key conclusions of the paper are,

i) The linear modulation range of PPM based 9-phase IM drive is improved by 15.4% as compared to sine PWM.
ii) With the proposed carrier phase PWMs (CPS-PWM1 and CPS-PWM2) the number of levels and harmonic profile of effective phase voltage are improved.
iii) The multilevel voltage generated by the proposed CPS-PWMs will improve the performance of PPM based IM drive.

The 5hp 9-phase PPMIM drive with proposed MLI scheme is validated by using the Ansys Maxwell as well as experimental prototype**.**

5. Appendix:

Rating of the machine: 5hp, Stator/rotor slots: 36/49, winding type: full pitch winding, coil pitch:9, DC link voltage: 70V, switching frequency: 2kHz, modulating frequency:50Hz.
Experimental prototype details: core length (L)/ airgap diameter (D)/: 130 mm/160 mm, length of airgap:1 mm.

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7. References

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