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Common Mode Voltage Reduction in Three Phase Inverter using Pre-Calculated Harmonic Eliminated PWM Method

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Abstract: Common Mode Voltage (CMV) produced in Pulse Width Modulated (PWM) inverters causes premature failure of the motor bearings. Therefore CMV has to be reduced. Pre-calculated Harmonic Eliminated PWM (PHEPWM) scheme is proposed to reduce the CMV in three phase inverter. The accurate switching angles have to be calculated by solving nonlinear equations. The switching angles for the pre-calculated harmonic elimination technique are calculated by using Newton-Raphson algorithm. The proposed modulation scheme is evaluated and tested at various switching frequencies for different modulation index. With this PHEPWM it is possible to eliminate the lower order harmonics, 5th, 7th , 11th, 13th, 17th, 19th, and 23rd from the inverter output voltage for any desired value of the fundamental component in for any desired modulation index. The CMV in inverter using PHEPWM method is compared with CMV produced using classical Sinusoidal PWM (SPWM) method.

Keywords: Common Mode Voltage (CMV), Pulse Width Modulated (PWM), Pre-calculated Harmonic Eliminated PWM (PHEPWM)

I. INTRODUCTION

Two level Voltage Source Inverters (VSI) are very widely used for converting input DC voltage to three phase AC output voltage of variable magnitude and frequency. High frequency inverters are used for many applications such as induction heating, dielectric heating, microwave heating, AC drives and also used in un-interrupted power supplies. To obtain voltage of required magnitude SPWM is widely used to generate the switching pulses because it is easy to generate SPWM pulses using simple control circuit. For each period, SPWM produces pulses of constant amplitude with variable pulse width. The pulse width is controlled to reduce its harmonic content. The CMV is measured between the midpoint of DC supply and the neutral point of a load. In ac motors drives CMV exists between the motor frame and the motor windings [1-2]. CMV generates bearing currents in induction motors [3-4]. These currents will damage the bearings. The high frequency CMV induces shaft voltage on the rotor side [5].

When the induced shaft voltage exceeds the breakdown voltage of the lubricant, it results in large bearing currents. This will damage the bearings which further leads to failure of motor. Several methods were proposed in the literature to reduce the CMV generated in VSI. These are topology dependent and differ in the control strategy of the 3ϕ inverter. The CMV can be reduced by using a small passive Electro Magnetic Interference (EMI) filter [6] or by adding an additional 4th leg to the inverter [7-8] or by introducing additional auxiliary switches in each leg [9-10]. But in all these approaches, additional external devices (passive/active) are used to reduce CMV. Therefore these methods add on to the converter size and cost. Introducing more switches will add on to more switching losses. Therefore a PHEPWM method which produces PWM signal based on the pre-calculated switching angles [11-18] is proposed in this paper for the reduction of CMV. To substantiate the merits of the proposed PHEPWM technique in which switching angles to eliminate the desired lower harmonic levels are calculated using Newton-Raphson method. Simulation study is carried at different switching frequencies for various modulation indices. Section 2 presents theory and analysis. PHEPWM method is described in Section 3I, Newton-Raphson algorithm to calculate the switching angles in explained in Section 4. Section 5 gives the simulation results and experimental validation is given in Section 6. The analysis is concluded in Section 7.

II. THEORY AND ANALYSIS

3ϕ VSI consists of three legs, each leg has two power switches as shown in Fig 1. The inverter can be operated in 180^0 conduction mode in one scheme each switch conducts for 180^0 or 120^0 conduction mode in switch each switch conducts for 120^0. The upper and lower switches of each le are complementary to each other. In 180^0 conduction mode, three switches will conduct at a time. It can be one from the upper group, the one which is connected to the positive of dc bus, and two from lower group which are connected to negative terminal of the supply or vice-versa. To obtain a cycle of output voltage the switching is done six times where switching is of the combination:- (S5 S6 S1)- (S6 S1 S2)- (S1 S2 S3) - (S2 S3 S4)-(S3 S4 S5)-(S4 S5 S6). The commutation takes place at every 60^0 and there are six commutations to get a cycle of output voltage.

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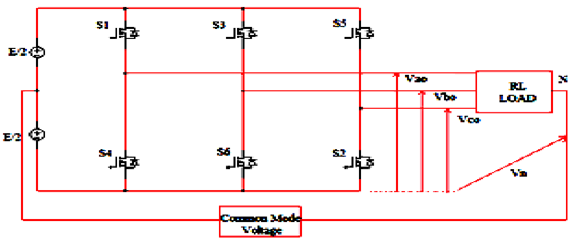

Fig. 1 Three phase VSI

CMV V_g is given by : $V_g = V_n - \frac{E}{2}$ **(1)**

Where,

Neutral Voltage $V_n = \frac{V_{a0} + V_{b0} + V_{c0}}{3}$ **(2)**

III. PRE-CALCULATED HARMONIC ELIMINATE PWM METHOD

In PHEPWM method notches are created on the square wave at pre-calculated angles to eliminate undesirable lower order harmonics. By applying proper notch angles we can control the fundamental output voltage and can eliminate undesirable lower order harmonics. By increasing the number of notch angles, more number of lower order harmonics can be eliminated. Positive half cycle of the inverter output with quarter wave symmetry is shown in Fig .2. In-order to eliminate *n* number of lower order harmonics, *(n+1)* notch angles have to be generated foe example to eliminate first three lower order harmonics, four notch angles α₁, α₂, α₃ and α₄ have to be calculated.

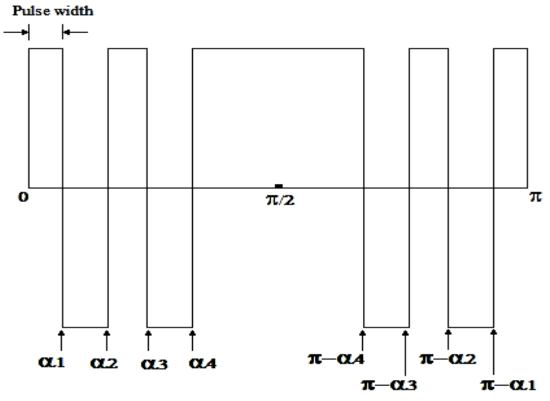

Fig. 2 Normalized inverter output voltage Va0

The general Fourier series for voltage is given by:

$$v(t) = \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t) \qquad \textbf{(3)}$$

Where

$$a_n = \frac{1}{\pi} \int_0^{2\pi} v(t) \cos(n\omega t) d\omega t \qquad \textbf{(4)}$$

$$b_n = \frac{1}{\pi} \int_0^{2\pi} v(t) \sin(n\omega t) d\omega t \qquad \textbf{(5)}$$

Since voltage waveform exhibits quarter wave symmetry only odd harmonics are present.

$a_n = 0,$

$$v(t) = \sum_{n=1}^{\infty} b_n \sin n\omega t \qquad \textbf{(6)}$$

Where

$$b_n = \frac{4}{\pi} \int_0^{\frac{\pi}{2}} v(t) \sin(n\omega t) d\omega t \qquad \textbf{(7)}$$

Assuming that the wave has unit amplitude, then

$$b_n = \frac{4}{n\pi}[1 + 2(-\cos n\alpha_1 + \cos n\alpha_2 - ..... + \cos n\alpha_k)]$$

$$b_n = \frac{4}{n\pi}[1 + 2\sum_{k=1}^{k} (-1)^k \cos n\alpha_k] \qquad \textbf{(8)}$$

Since the neutral point is isolated, third order harmonics and multiples of third order harmonics are not present, so n takes the odd values 5, 7, 11, 13, 17, 19, 23....etc. Thus, the following transcendental equations should be solved simultaneously to obtain the appropriate switching angles.

To control the magnitude of the 1st harmonic component,

$$b_1 = \frac{4}{1 \times \pi}[1 + 2\sum_{k=1}^{k} (-1)^k \cos \alpha_k] = m_a$$

To eliminate the undesired lower order harmonics,

$$b_n = \frac{4}{n\pi}[1 + 2\sum_{k=1}^{k} (-1)^k \cos n\alpha_k] = 0$$

1. 1. Case study 1

The objective is to eliminate the 5th, 7th, and 11th harmonics and to control the fundamental component .For that,1st harmonic is set to any modulation index (m_a) and other lower order harmonics such as 5th, 7th & 11th are set to zero. Newton Raphson algorithm can be used to solve these transcendental nonlinear equations.

$$b_n = \frac{4}{n\pi}[1 + 2\sum_{k=1}^{4} (-1)^k \cos n\alpha_k]$$

$$where, n = 5,7,11$$

2. 2. Case Study 2

The objective is to eliminate the 5th, 7th, 11th, 13th, 17th, 19th, and 23rd harmonics and to control the fundamental component. For that, 1st harmonic is set to any modulation index (m_a) and other lower order harmonics such as 5th to 23rd are set to zero. Newton Raphson algorithm can be used to solve these transcendental nonlinear equations.

$$b_n = \frac{4}{n\pi}[1 + 2\sum_{k=1}^{8} (-1)^k \cos n\alpha_k]$$

$$where, n = 5,7,11,13,17,19,23$$

IV. NEWTON- RAPHSON ALGORITHM

1) Set initial values for α

$$\alpha^j = [\alpha_1^j, \alpha_2^j, \alpha_3^j .... \alpha_k^j]$$

$$\text{With } j = 0$$

$$F(\alpha^j) = F^j$$

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Where F is the vector format of the nonlinear transcendental equations.

2) Linearize the above equation about α j

$$F^{j} + \left[\frac{\partial f}{\partial \alpha}\right]^{j} d\alpha^{j} = T$$

Where, T is the amplitude the harmonic components.
j is the functions connecting harmonics with switching angles.

$$J = \left[\frac{\partial f}{\partial \alpha}\right] = \begin{bmatrix} \frac{\partial f_1}{\partial \alpha_1} & \frac{\partial f_1}{\partial \alpha_2} & \cdots & \frac{\partial f_1}{\partial \alpha_3} \\ \frac{\partial f_2}{\partial \alpha_1} & \frac{\partial f_2}{\partial \alpha_2} & \cdots & \frac{\partial f_2}{\partial \alpha_3} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial f_K}{\partial \alpha_1} & \frac{\partial f_K}{\partial \alpha_2} & \cdots & \frac{\partial f_K}{\partial \alpha_K} \end{bmatrix} \qquad d\alpha^{j} = [d\alpha_1^{j},$$

3) Solve $d\alpha^{j}$

$$d\alpha^{j} = INV\left[\frac{\partial f}{\partial \alpha}\right]^{j} (T - F^{j})$$

4) Change the initial values of each step by

$$\alpha^{j+1} = \alpha^{j} + d\alpha^{j}$$

5) Repeat the process, step 2 to step 4 until $d\alpha^{j}$ satisfied the desired degree of accuracy.

V. SIMULATION RESULTS

The proposed PHEPWM method is validated with the help of simulation results. The simulation is carried out in PSIM environment. The pulses generated using SPWM and PHEPWM methods are applied to the inverter which feeds RL load (200Ω, 2.6H). The DC bus voltage E is kept at 28V. The simulation circuit is shown in Fig 3.

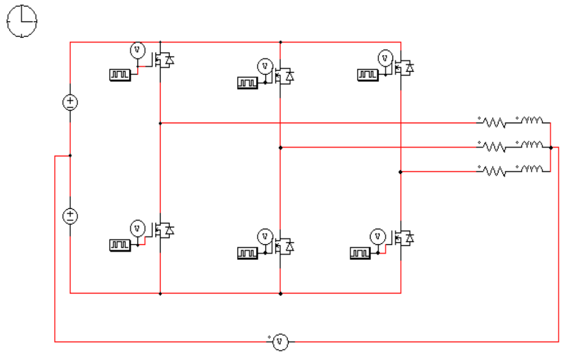

Fig. 3 Simulation model of three phase inverter using PHEPWM

The Newton-Raphson method is used to calculate appropriate notch angles to eliminate the low-order odd harmonics from the inverter voltage waveform. The switching angles and switching pulses to eliminate first three lower order harmonics are presented in Table 1 and Fig. 4 respectively. The switching angles and switching pulses to eliminate first seven lower order harmonics are shown in Table 2 and Fig. 5 respectively.

Table. 1 Switching angles computed using Newton-Raphson algorithm to eliminate 5th , 7th and 11th harmonics at m_a= 0.8

Notch/Switching Angles	Values
α1	11.0481
α2	24.2476
α3	40.9531
α4	50.2758

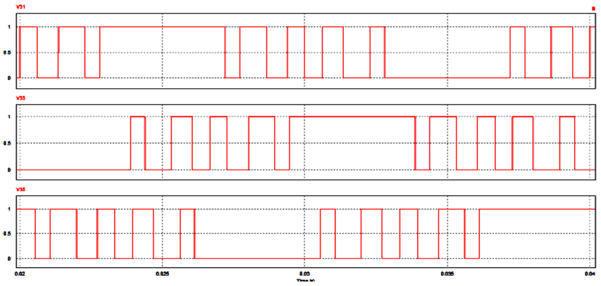

Fig. 4 Control signals: S1, S3, and S5 to eliminate 5th, 7th and 11th harmonics

Table. 2 Switching angles computed using Newton-Raphson algorithm to eliminate 5th , 7th , 11th , 13th , 17th ,19th and 23rd harmonics at m_a= 0.8

Switching Angles	Values
α1	5.45524
α2	13.4179
α3	20.5738
α4	26.8577
α5	35.5179
α6	40.6759
α7	50.3813
α8	54.9553

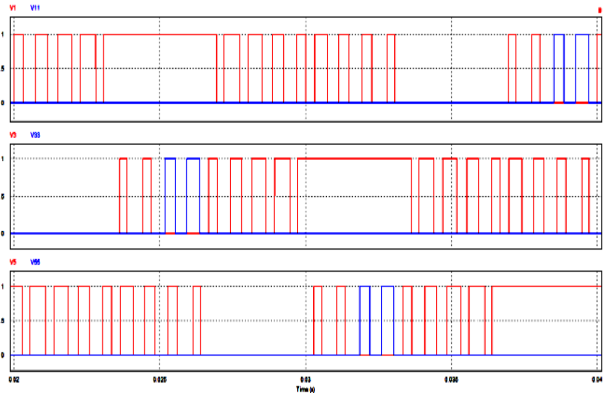

Fig. 5 Control signals: S1, S3, and S5 to eliminate 5th, 7th, 11th, 13th, 17th, 19th and 23rd harmonics

The simulation results for PHEPWM are given below:

The line, phase voltages and CMV are shown in Fig.6, Fig.7 & Fig.8 respectively. The modulation index is 0.8. The FFT spectrum of the line voltage is shown in Fig. 9 and the CMV for various switching frequencies is indicated in Table 3.

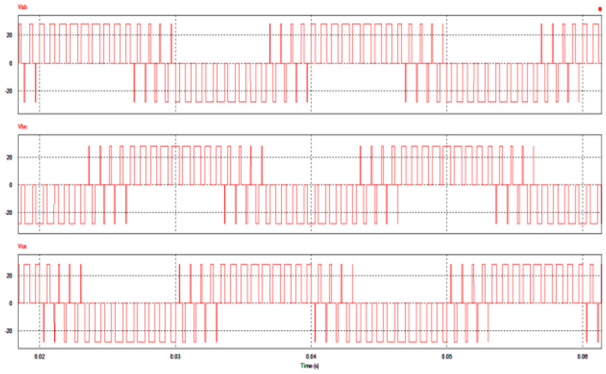

Fig. 6 Line voltages (PHEPWM strategy eliminating the 5th to 23rd harmonics and m_a=0.8)

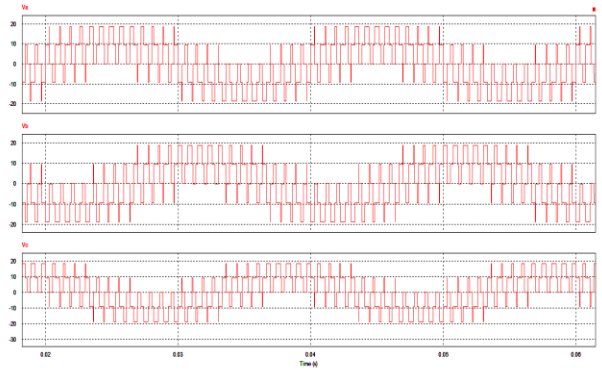

Fig. 7 Phase voltages (PHEPWM strategy eliminating the 5th to 23rd harmonics and m_a=0.8)

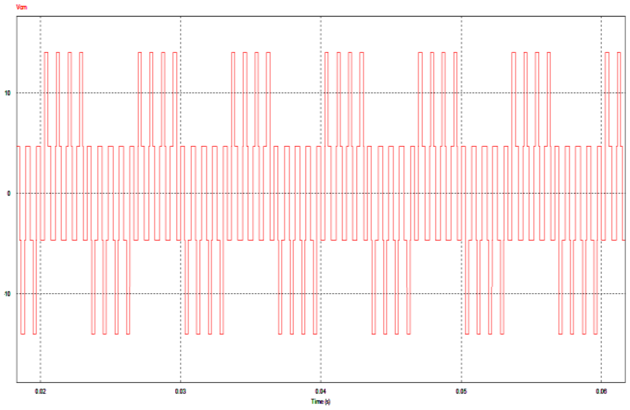

Fig. 8 CMV (PHEPWM strategy eliminating the 5th to 23rd harmonics and m_a=0.8)

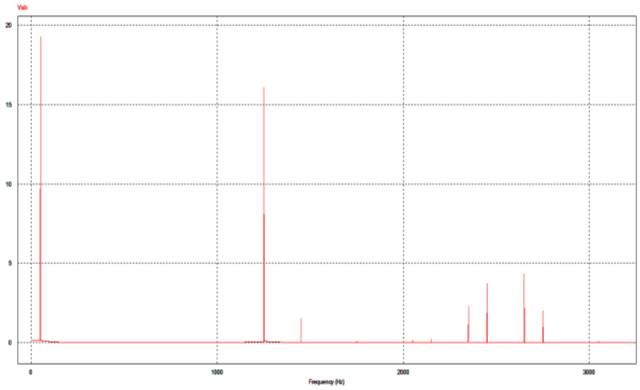

Fig. 9 Harmonic spectrum of the inverter line voltage Vab (PHEPWM strategy eliminating the 5th to 23rd harmonics and m_a=0.8)

Table. 3 Line voltages and CMVs for PHEPWM method at m_a=0.8

Switching Frequency (Hz)	CMV (V)	Line Voltge, V_{ab} (V)	Line Voltge, V_{bc} (V)	Line Voltge, V_{ca} (V)
50	8.27	19.28	19.23	19.27
750	8.2	19.34	19.34	19.34
1050	8.2	19.34	19.34	19.34
1650	8.2	19.34	19.34	19.34
3150	8.2	19.34	19.34	19.34
5250	8.18	19.36	19.36	19.36
8250	8.13	19.43	19.43	19.43
10000	8.2	19.34	19.34	19.34
15000	8.16	19.39	19.39	19.39
21000	8.06	19.51	19.51	19.51
25000	8.02	19.57	19.57	19.57

The line, phase voltages, and CMV using conventional SPWM method are shown in Fig.10, Fig.11 & Fig.12 respectively. The modulation index is kept as 0.8 and switching frequency is taken as 1050Hz. The FFT spectrum of the line voltage is shown in Fig.13 and the CMV for various switching frequencies are indicated in Table 4.

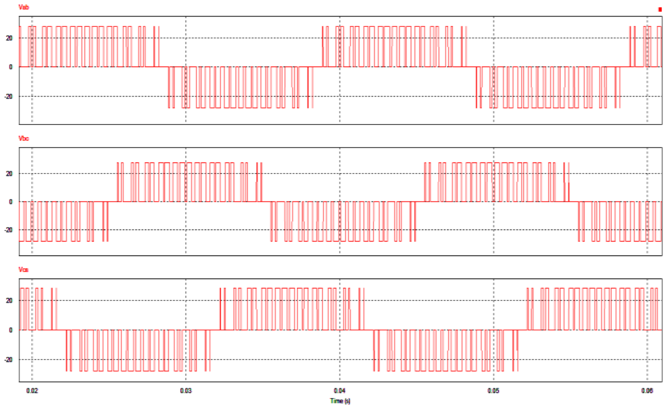

Fig. 20 Conventional SPWM switching based-Line voltages at Fs=1050Hz and ma=0.8

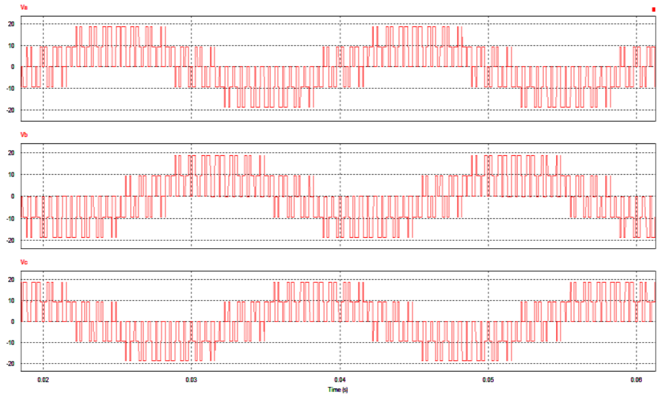

Fig. 13 Conventional SPWM switching based-Phase voltages at F_s=1050Hz and m_a=0.8

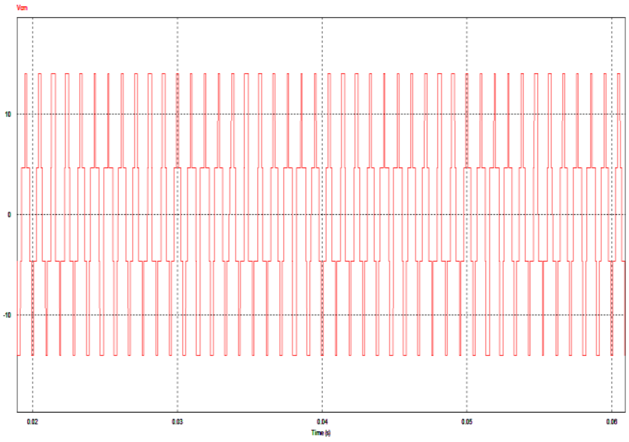

Fig. 42 Conventional SPWM based switching CMV at F_s=1050Hz and m_a=0.8

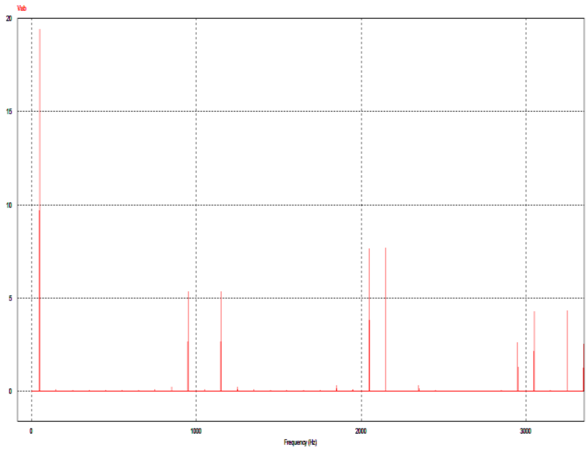

Fig. 53 Conventional SPWM based switching Harmonic spectrum of the inverter line voltage Vab at F_s=1050Hz and m_a=0.8

Table. 4 SPWM switching- CMVs and line voltages for m_a=0.8

Switching Frequency (Hz)	CMV (V)	Line Voltge, V_{ab} (V)	Line Voltge, V_{bc} (V)	Line Voltge, V_{ca} (V)
750	8.91	18.4	18.4	18.4
1050	8.9	18.42	18.41	18.38
1650	8.9	18.41	18.37	18.42
3150	8.9	18.43	18.4	18.38
5250	8.89	18.41	18.46	18.4
8250	8.9	18.39	18.41	18.42
10000	8.88	18.42	18.45	18.42
15000	8.85	18.48	18.48	18.47
21000	8.85	18.48	18.44	18.52
25000	8.53	18.93	18.93	18.93

Table 5 gives switching angles to eliminate 7 lower order harmonics for various modulation indices and Table 6 gives the CMVs in both Conventional SPWM and PHEPWM methods for various modulation indices.

Table. 5 Swiching angles to eliminate seven lower order harmonics- for various amplitude modulation indices

m_a	0.4	0.5	0.6	0.7	0.8	0.9
α1	3.45176	3.9863	4.49666	4.98628	5.45524	5.90024
α2	15.288	14.8265	14.3622	13.8937	13.4179	12.9289
α3	18.9754	19.4131	19.8315	20.2229	20.5738	20.86
α4	29.3377	28.7524	28.1494	27.5219	26.8577	26.1341
α5	33.6906	34.19	34.6687	35.1173	35.5179	35.8329
α6	43.3802	42.7446	42.0895	41.4058	40.6759	39.8631
α7	48.1639	48.7363	49.3	49.8512	50.3813	50.8702
α8	57.534	56.9082	56.2739	55.6262	54.9553	54.2394

Table. 6 CMVs for various amplitude modulation indices - Conventional SPWM and PHEPWM

Amplitude modulation index ma	CMV in PHEPWM method (V)	CMV in SPWM method (1050Hz) (V)
0.4	10.56	11.66
0.5	10	11.04
0.6	9.42	10.37
0.7	8.67	9.67
0.8	8.27	8.90
0.9	7.73	8.06

It is observed from the results that the CMV has reduced and the line voltage has increased in the PHEPWM method for all switching frequencies and modulation indices, when compared to the SPWM. And it is also observed that, the number of the switchings of the semiconductor switches (MOSFET) is less for PHEPWM method compared to the SPWM method so switching losses are less. From the harmonic spectrum of line voltage it is found that in PHEPWM method the low frequency harmonics have eliminated, so the required size of external filter is small.

VI. EXPERIMENTAL RESULTS

The proposed PHEPWM method to eliminate first seven lower order harmonics method and the SPWM method had been tested using a RL load (200Ω, 2.6H). The modulation index was kept at 0 .8 and the switching frequency for SPWM is 1050 Hz. The DC bus voltage E was kept as 28V. Pulses for the switches of inverter are obtained from PIC16F877A microcontroller. Fig.14. shows the experimental setup.

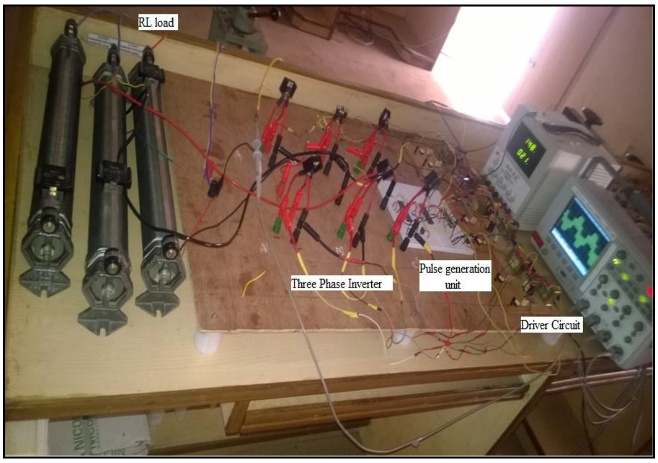

Fig. 14 The experimental setup

The experimental results for Normal SPWM are given below:

The switching pulse obtained from PIC16F877A microcontroller is given Fig. 15. The line voltages, phase voltages , and CMV are shown in Fig.16, Fig.17 & Fig.18 respectively. The Harmonic spectrum of the Line voltage shown in Fig. 19.

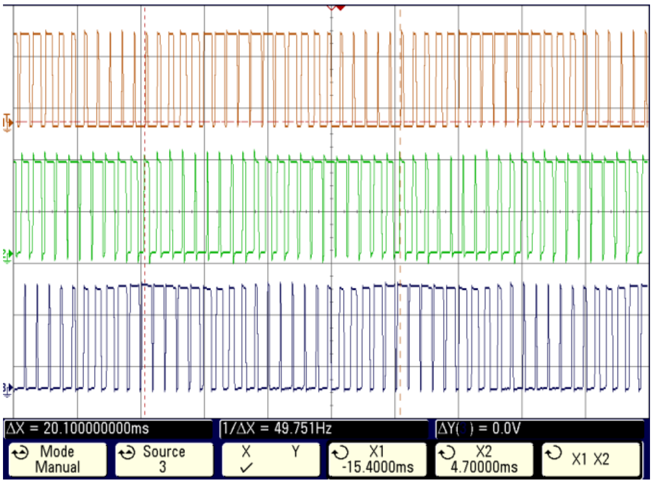

Fig. 15 Switching pulses obtained from PIC16F877A microcontroller (SPWM method)

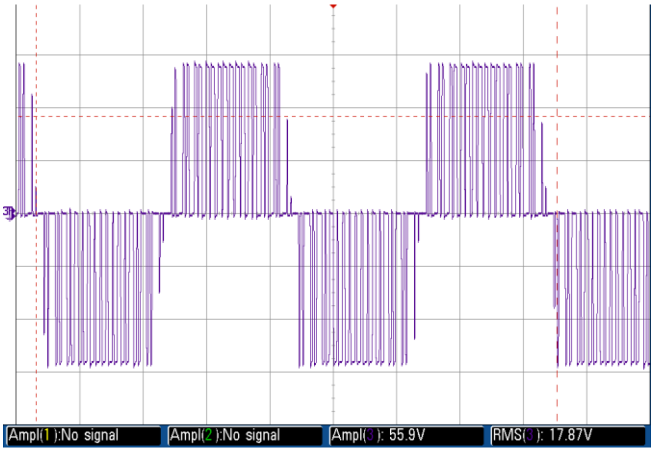

Fig. 66 Line voltage (Conventional SPWM strategy, 17.87V)

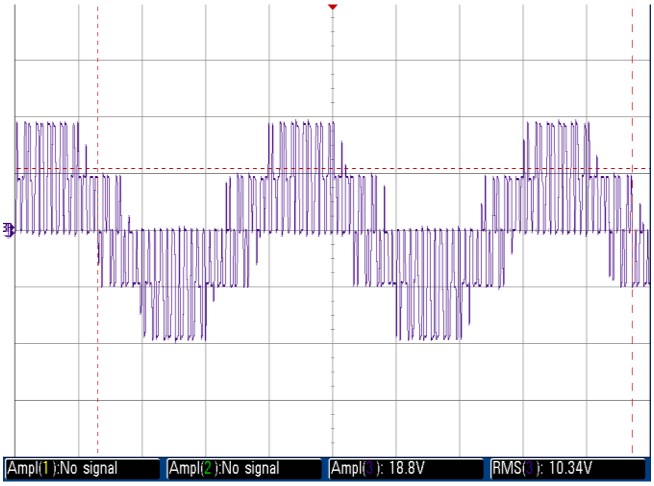

Fig. 77 Phase voltage (Conventional SPWM strategy, 10.34)

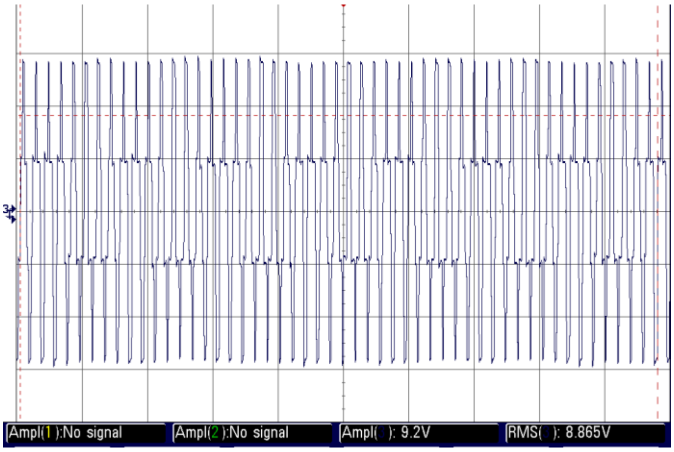

Fig. 88 Common Mode Voltage for Conventional SPWM method= 8.86)

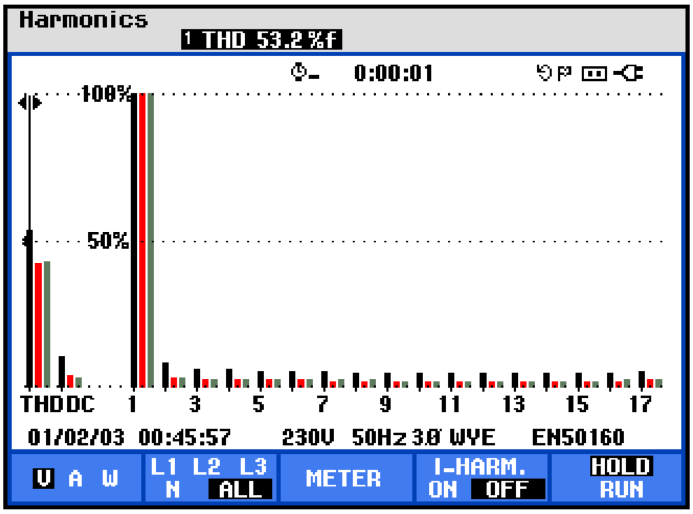

Fig. 99 Harmonic spectrum of the inverter line voltage Vab for Conventional SPWM strategy at F_s =1050Hz and m_a=0.8

The experimental results for PHEPWM are shown from Fig.21 -24.

The switching pulse obtained from PIC16F877A micro controller is given Fig. 20. The line voltages, phase voltages and CMV are shown in Fig. 21, Fig. 22 & Fig. 23 respectively. The modulation index is taken as 0.8. The Harmonic spectrum of the Line voltage is shown in Fig. 24.

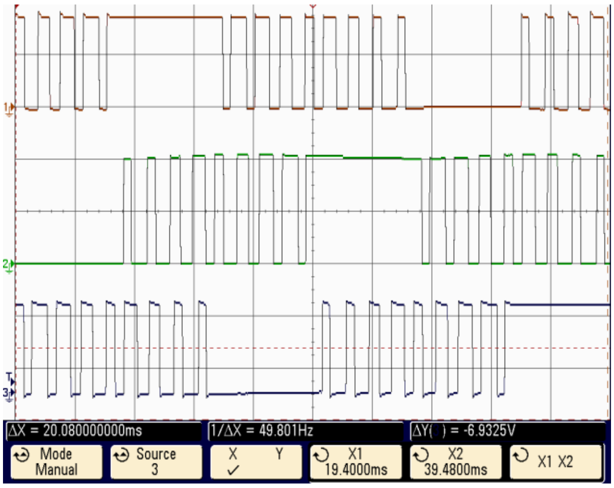

Fig. 20 Switching pulses obtained from PIC16F877A microcontroller (PHEPWM method)

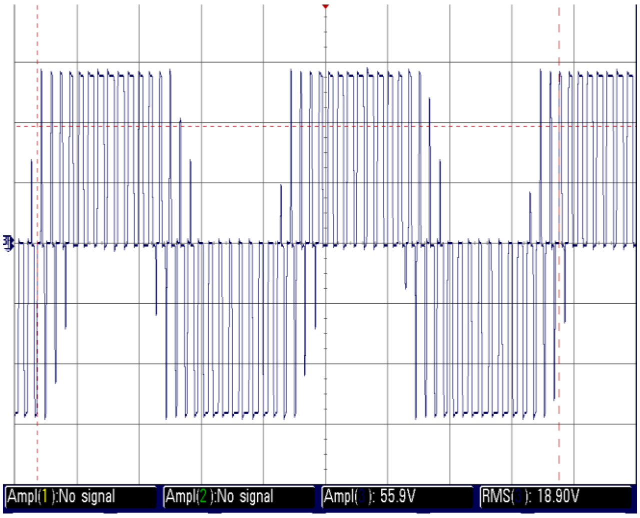

Fig. 21 Line voltage (PHEPWM strategy, 18.90V)

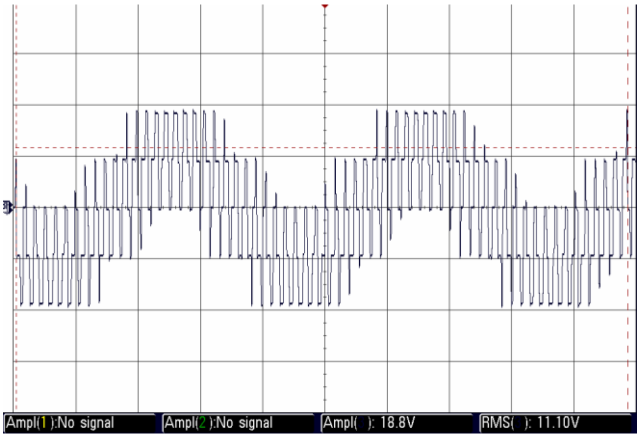

Fig. 22 Phase voltage (PHEPWM strategy, 11.10V)

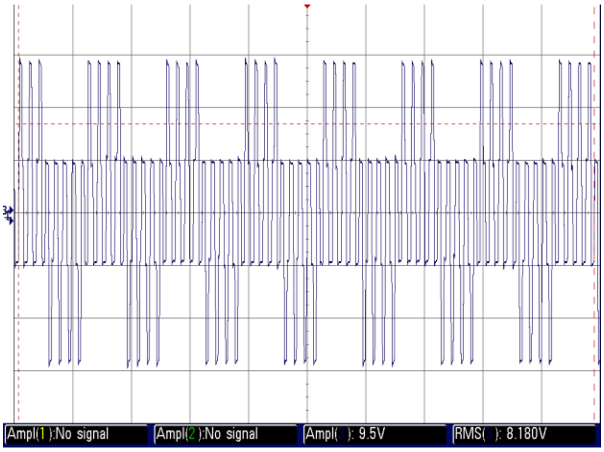

Fig. 23 Common mode voltage (PHEPWM strategy, 8.180V)

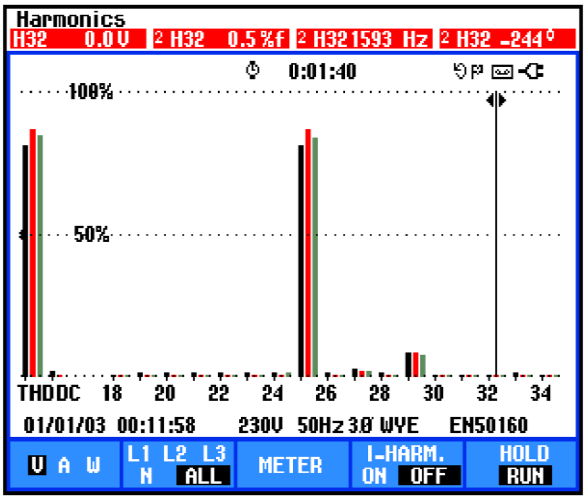

Fig. 24 Harmonic spectrum of the inverter line voltage Vab (PHEPWM strategy eliminating the 5th to 23rd harmonics and m_a=0.8)

VII. CONCLUSION

A pre-calculated switching method to reduce the common mode voltage between the neutral point of load and the middle point of the DC source in three phase inverter was proposed in this paper. The CMV for conventional SPWM and PHEPWM at various switching frequencies and modulation indices were observed. The PHEPWM method reduces the CMV over wide range of switching frequency and modulation index. The work can be further extended for the three phase inverter fed induction motor.

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