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Quality Improvement of VSI fed to Five-Phase Induction Motor with FHI Control Technique

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Abstract

The best part of five-phase machine is the lowest number of phase which possesses all advantages of the multiphase machine. Hence it is prime important to study the quality output of the inverter fed to the five-phase induction motor. Output of the five-phase inverter controlled by using pulse width modulation technique (PWM) and with input dc voltage (Vdc), the peak of the fundamental component is half of Vdc, when modulation index (m) is one. If fifth harmonic injected (FHI-PWM) sinusoidal reference wave is used, the peak of the fundamental component of the voltage on the AC side can be increased by increasing the modulating index (m) towards unity without reaching over-modulating area. So here the analysis of FHI-PWM and advantages of FHI-PWM over PWM control technique have been presented. The simulation and experimental test is carried out on five-phase induction motor with quality waveform. The use of FHI-PWM, the output voltage is increased up to 6.18 percent more than that of a PWM with reduction in lower order harmonics and Total harmonics distortion (THD) for unity modulating index or over modulation case.

Keywords: Lower Order Harmonics, FHI-PWM, PWM, Five Phase Inverter, Total Harmonic Distortion.

INTRODUCTION

Recently in many industrial applications, with the variable voltage variable frequency multi-phase induction motor is used, like locomotive traction, cement factory, electric and hybrid lectric vehicles and other high power industries[1]. Also multi-phase motors has many advantages over traditional three phase induction motor such as less torque pulsation with reduced amplitude and frequency, reduction in magnitude of current per phase without increment in voltage per phase, high reliability, DC link current ripple get reducess[2]. Use of the control technique depends quality of the output waveform of the inverter For a PWM control technique.The voltage gain can be determine by, the ratio of the peak of the fundamental output voltage on AC side of inverter to the DC voltage input. The peak of the fundamental output voltage by using the conventional PWM technique reduces 87% of the DC input voltage [1], [2].

In five phase induction motor drive, five phase inverter is required to generate sinusoidal output voltages so that there should be sinusoidal MMF distribution in the motor. Hence, the reference voltage control scheme ensure that there should be minimum undesirable lower order harmonics in the voltage as well as in the motor current to avoid the losses. So by utilizing the fifth- harmonic injection component in control technique increase stator current, which enhances the torque.

New control techniques have been used to increase the DC bus utilization of input with quality waveform. The intelligent pattern of PWM pulse can amplify the fundamental component of output voltage. At middle portion of the pulse waveform, expanded width due to 5^{th} harmonic injected reference waveform tends to amplify the fundamental output voltage about 6.18% of the conventional PWM [3],[4]. The lower order harmonics have been less in magnitude for unity modulating index as well as over modulation in FHI-PWM than that of conventional PWM technique. This paper shows the simulation as well as hardware results for comparison.

FIVE PHASE INVERTER AS FIVE PHASE SUPPLY SYSTEM

Five Phase System

In a balanced 5-phase system phase voltages magnitude are equal with phase angles equally spaced from each other is of 72^0. For five phase star connected system as shown in Fig. (1), five voltage phasor rotate in space with 360 ÷ 5 = 72° degree phase shift from each other. With phase A to neutral voltage V_{AN} is taken as reference, V_{BN} is lagging V_{AN}, V_{CN} is lagging V_{BN}, V_{DN} is lagging V_{CN} and V_{EN} is lagging V_{DN}. Let $V_L(adj.)$ be the voltage between any two consecutive pair of lines, $V_L(alt.)$ be the voltage between any two alternate pair if lines and $V_{Ph} = V_{AN} = V_{BN} = V_{CN} = V_{DN} = V_{EN}$ [5].

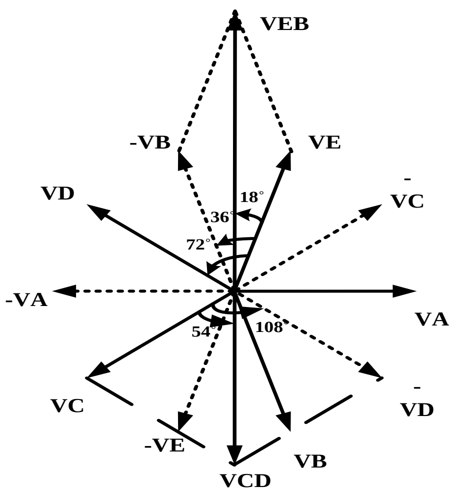


Figure 1: Phasor representation of Five-phase voltages

For the balanced phase voltages shown in Fig. (1), it is observed that $V_L(adj.) = 1.175 \times V_{Ph}$,$V_L(alt.) = 1.902 \times V_{Ph}$ and $I_L(adj.) = I_L(alt.) = I_{Ph}$ Where $I_L(adj.)$ is the adjacent line current, $I_L(alt.)$ is alternate line current and I_{Ph} is phase current. The power per phase is $P = V_{Ph} I_{Ph} \cos \emptyset$ and the total power is the sum of the power in each phase [5]

Five Phase Inverter

A circuit diagram of five-phase VSI is as shown in Fig. (2). It converts input DC voltage to variable a five-phase voltage output.[6-8].

To get the inverter output AC voltage, the simplest PWM control technique is of comparison of the five sinusoidal reference functions (modulating signal) with a high frequency common triangular carrier function. The DC bus voltage applied at output is whether negative or positive depends upon larger or smaller modulating signal than the magnitude of carrier waveform. The average output voltage applied to the load is in proportion with the amplitude of the modulating function during the period of a triangular waveform. The resultant saw off square shaped waveform has a replication of the required waveform [8]. The modulation index m is as given by (1)

$$\boldsymbol{m} = \frac{A_r}{A_c} \qquad (1)$$

where A_r is reference signal amplitude and A_c is carrier function amplitude. [1].

Use of PWM control technique with even unity modulating index, the inverter output voltage has a limit of 0.5Vdc. However, for the modulating index more than 1, the width of pulse is not a sinusoidal function and it appears large lower order harmonics in inverter leg voltages. Such as 3rd, 5th, 7th, 9th and 11th. The magnitude of harmonic is given by $V_n = \frac{1}{n^{th}} \times V_1$.

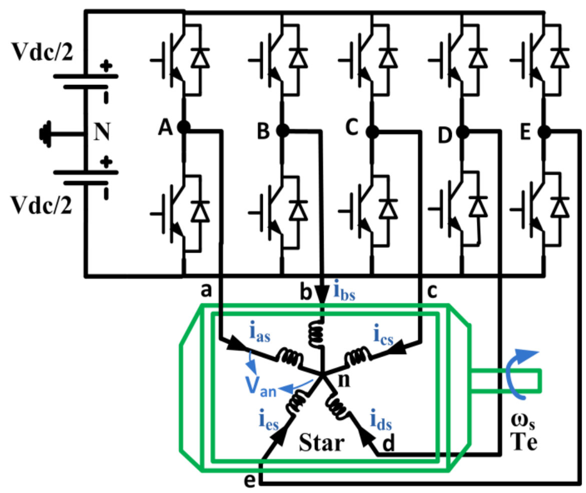


Figure 2: Five-phase voltage source inverter with induction motor.

Since magnitude is inversely proportional to the order of harmonics, the lower order harmonics have considerable effect on motor, whereas higher order harmonics are negligible due to low voltage magnitude. Due to presence of lower order harmonics, motors experience hysteresis and eddy currents losses in the iron core of the motor as they are in proportion with the frequency. Since the harmonics are at higher frequencies than power frequency, they produce higher losses in motor core. This increases heating of the motor core, which can reduce the life of the motor [9-11].

Algorithm for calculation of Fifth Harmonic Injected Component

The inverter output voltage is of 0.5 Vdc for unity modulation index by using PWM control technique. To increase the output voltage by increasing the modulation index increases i.e. running inverter in over modulation, increases the lower order harmonics. Hence if the PWM control technique is used, in the application of induction motor drive, the AC output voltage of inverter not be that much enough to run the motor with rated condition. In this situation, the machine worked with de-rated condition and the magnitude of torque gets reduces. For amplification of the output voltage waveform with the inverter controlled by PWM, the injection of fifth-harmonic is carried out in the reference signal [8]. In this technique the reference modulating signal is not pure sinusoidal but combination of fundamental and a fifth harmonic component. It is implemented just like PWM. The fundamental and a fifth harmonic component is in phase opposition as shown in fig (3). [12], [13].

The fundamental component in addition with the fifth-harmonic component, resultant is reduction of the peak of the reference modulating function. Therefore the resultant modulating function can be increased above the 0.5 *Vdc* and which increases the output voltage of the inverter. (See fig. 3). It is found that, the output voltage of the five-phase inverter fifth harmonic component is zero, as in case of three phase inverter where third harmonic component is zero. Hence just like third harmonic injection technique, fifth harmonic injection is possible with the five phase inverter so that voltage does not contain unwanted lower order harmonics and the quality of the waveform increases. [3], [8], [14].

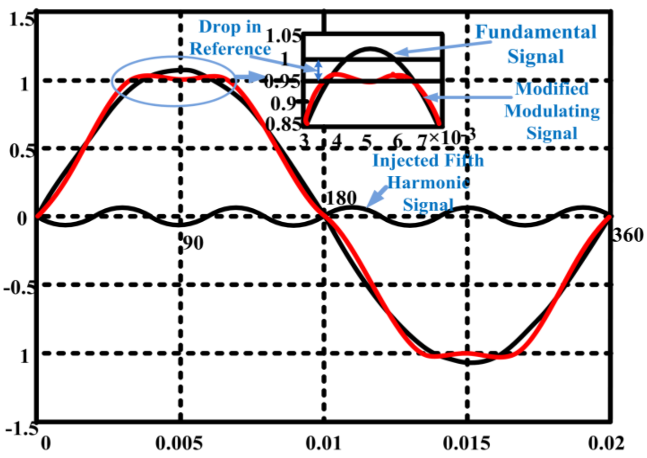


Figure 3: Fifth Harmonic Injected Pulse Width Modulation

The reference modulating signals are given as

$$V_{ao} = 0.5M_1 * V_{dc}\cos(\omega t) + 0.5M_5 * V_{dc}\cos(5\omega t)$$

$$V_{bo} = 0.5M_1 * V_{dc}\cos(\omega t - 2\pi/5) + 0.5M_5 * V_{dc}\cos(5\omega t)$$

$$V_{co} = 0.5M_1 * V_{dc}\cos(\omega t - 4\pi/5) + 0.5M_5 * V_{dc}\cos(5\omega t) \quad (2)$$

$$V_{do} = 0.5M_1 * V_{dc}\cos(\omega t + 4\pi/5) + 0.5M_5 * V_{dc}\cos(5\omega t)$$

$$V_{eo} = 0.5M_1 * V_{dc}\cos(\omega t + 2\pi/5) + 0.5M_5 * V_{dc}\cos(5\omega t)$$

Where, M_1 and M_5 are the amplitude of the fundamental and 5th harmonic component respectively. There is no effect of the 5th harmonic component on the value of the reference function if, $\omega t = (2k+1) * \pi/10$.

Since, $\cos\left(\frac{5(2k+1)*\pi}{10}\right) = 0$, for all odd k.

Hence to get the value of M_5 by making the 5th harmonic component zero which is the amplitude of the reference function. From (2), the feasible value of the fundamental reference peak when the reference voltage reaches at maximum is,

$$\frac{dV_{ao}}{dt} = -0.5 * M_1 V_{dc}\sin(\omega t) - 0.5 * 5M_5 * V_{dc}\sin(5\omega t) \quad (3)$$

This gives,

$$M_5 = -M_1 * \frac{\sin(\pi/10)}{5}\ ; \quad \omega t = \pi/10 \quad (4)$$

The maximum modulation index can be determined as

$$|V_{ao}| = |0.5M_1 V_{dc}\cos(\omega t) - 0.5\frac{\sin(\pi/10)}{5} M_1 V_{dc}\cos(3\omega t)$$

$$and\ |V_{ao}| = 0.5V_{dc} \quad (5)$$

The above equation gives

$$M_1 = \frac{1}{\cos(\pi/10)}\ ; \omega t = \pi/10 \quad (6)$$

With the injection of 6.18% of 5th harmonic with the fundamental component, the fundamental output voltage is increased up to 5.15% more than the conventional carrier-based PWM. The output voltage now amplifies to 0.5257Vdc. When 6.18% of 5th harmonic is injected into the reference fundamental sinusoidal wave, the peak of modified signal has reduction, giving more scope for enhancing the reference and increasing the output of the inverter [8].

SIMULATION MODEL AND EXPERIMENTAL SETUP

Simulation Model and the Results of FHI-PWM Five – Phase Inverter

The mathematical model of five-phase inverter-motor is formulated and then simulated using MATLAB/SIMULINK software. The control techniques used for inverter are PWM and FHI-PWM alternately. The quality of the voltage and current waveform is found by doing THD analysis and finding of lower order harmonics of star connected induction motor for both control technique. The variation in percentage of

THD and lower order harmonics are carried out for both the control technique.

Table II: Parameters used for simulation and experimental results:

Switching frequency	10 KHz
Fifth Harmonic Wave	0.0618/0.06489 V
Carrier Amplitude Signal (Ac) for both the cases	1.0 V.
Modulating Signal Amplitude (Am): PWM and FHI-PWM fundamental wave	1/1.05 V

Here the simulation results are shown for 0.08 seconds. The simulation is performed for modulation index from 0.05 to 1.05 for both the control techniques. Fig. (5) show the simulation results of inverter. Signal (1) shows the phase voltage for star connected stator winding. Signal (2) shows adjacent line voltage. Signal (3) shows alternate line voltage and Signal (4) shows the line current of motor.

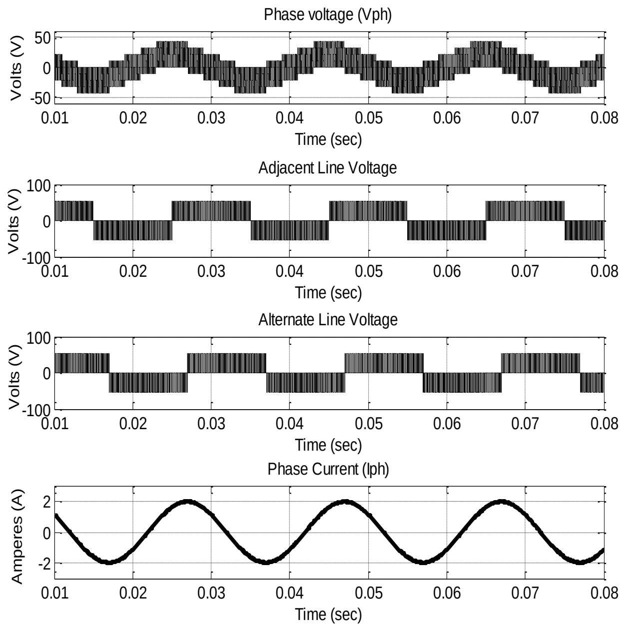


Figure 4: Simulation Inverter output: (1) Phase voltage, (2) Adjecent Line voltage, (3) Alternate Line Voltage, (4) Line Current

Experimental Set Up and Results of FHI-PWM Five –Phase Inverter

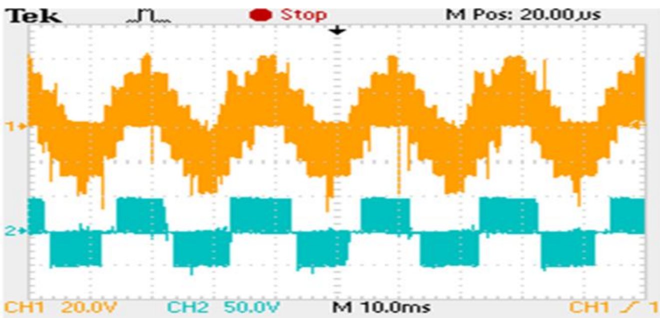
The laboratory test has been performed on five –phase induction motor supplied through five phase inverter with various measurement instruments. The AC-DC converter is composed of a controlled PWM controller which provides variation of the switching frequency. The dsPIC33EP256MU810 MICROCHIP Digital Signal Controllers offer simple microcontroller DSP. This controller has 12 PWM outputs, 83 I/O pins, 2 ADC modules with 32 channels. It can control two different five-phase inverter, as five phase inverter needs 10 gate signals. By using dsPIC33EP256MU810 for gate signals the fundamental output voltage is obtained with different pairs of dc voltage and modulating index (*m)* values which can be changed by controller programming. Fig. (5) shows the experimental setup of Five-Phase inverter fed induction motor [15].

The five-phase test motor has 1 Hp squirrel cage symmetrically distributed induction motor. It has r_s = 0.499 Ω, r_r = 0.926 Ω, Lls = 2.7 mH, Llr = 2.7 mH, Lm = 223mH, rotor inertia (J) = 0.047 kg-m2 and P = 2. four-pole squirrel cage induction motor. The stator was made of laminated magnetic steel [15]. The rated value of the motor is shown in Table 1.

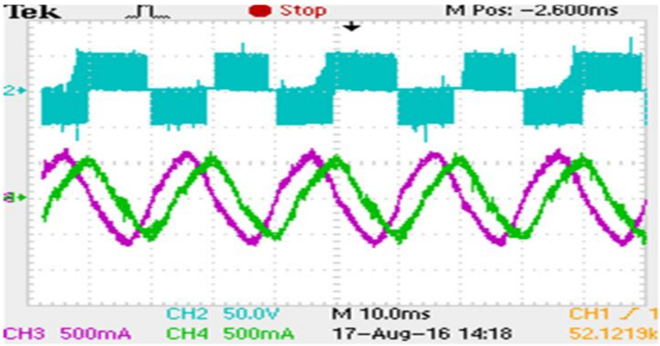
Table I1: Main Parameter of Test Motor

Quantity	**Value**	**Unit**
Slip	4 %	
Phase Voltage	200	V
Pole Number	4	-
Rotational Speed	1460	Rpm

Figure 5: Experimental Setup of Five-Phase inverter-motor circuit



(a)



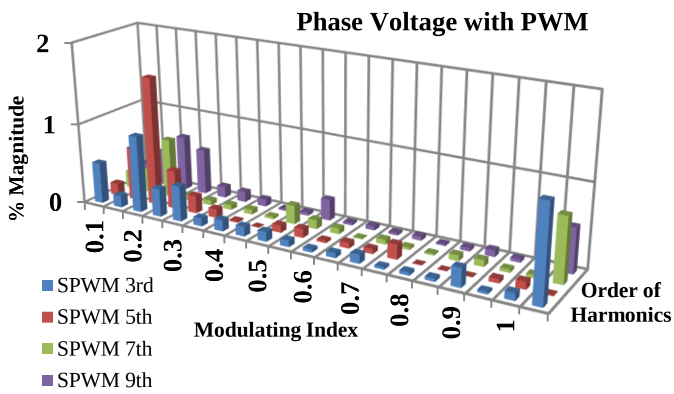
(b)

Fig. 6 Experimental Results (a) Phase voltage,and Adjecent Line voltage, (b) Alternate Line Voltage and Line Current

For the experimental setup mentioned above, the inverter experimental results are taken as phase voltage, adjacent line voltage, alternate line voltage and line current for star connected stator winding. Here the experiment has been performed using both control techniques. Fig. (6) shows experimental results captured with the help of Digital Storage Oscilloscope (DSO).

FFT Analysis

The FFT analysis is carried out for voltages with both PWM and FHI-PWM control technique. For this purpose FFT block of powergui unit is used. The lower order harmonics for both control technique in the output voltage of the inverter are compared and shown for modulation index from 0.05 to 1.05. For the comparison, bar charts are developed using Microsoft Excel. Fig. (7) shows the FFT analysis of variation of magnitude of lower order harmonics for different voltages with change in modulation index for PWM control technique. Fig. (8) shows the FFT analysis of variation of magnitude of lower order harmonics for different voltages with change in modulation index for FHI-PWM control technique.



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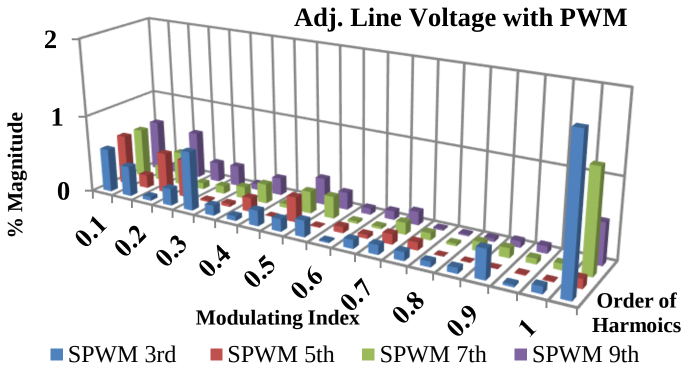

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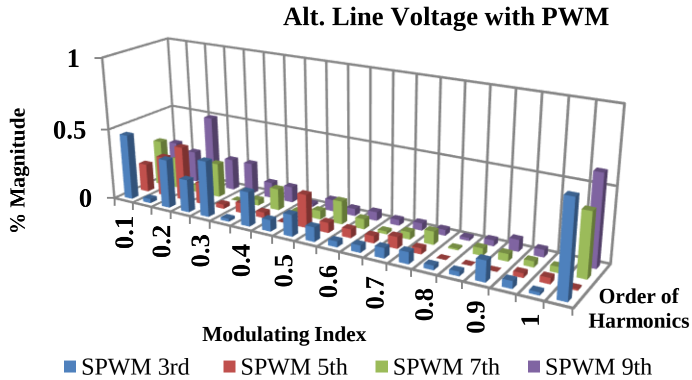
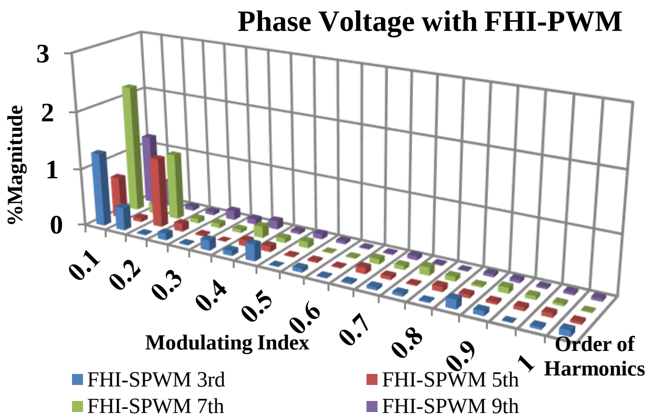


(c)

Fig.ure 7: FFT analysis of variation of lower order harmonics with modulating index for PWM: (a) Phase voltage, (b) Adjecent Line voltage, (c) Alternate Line Voltage



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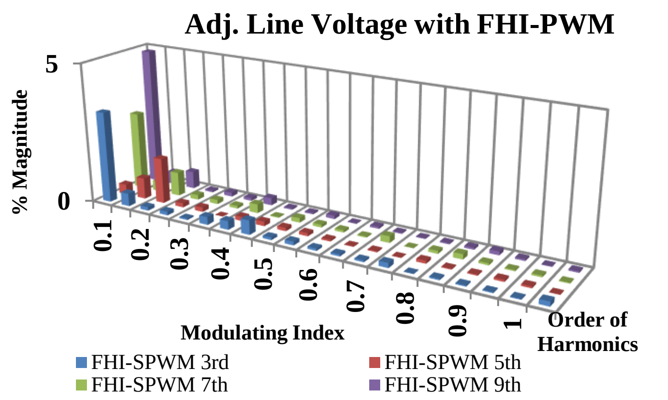

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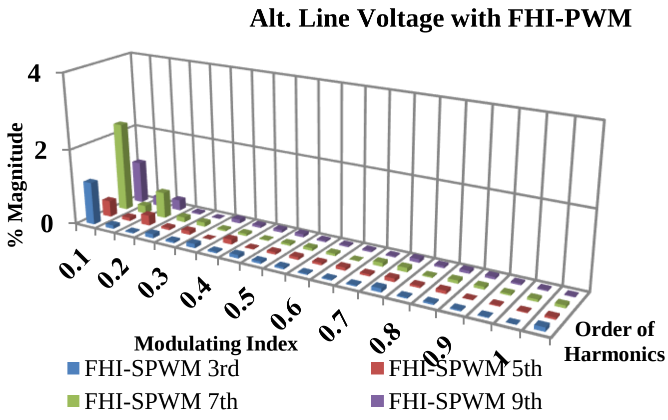
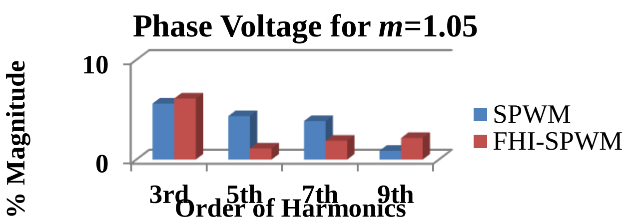


(c)

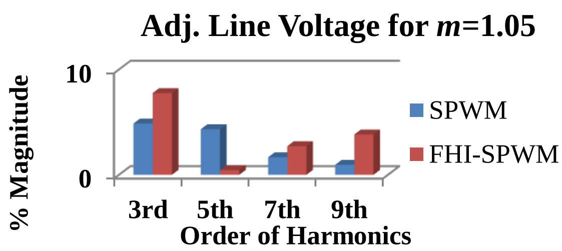
Figure 8: FFT analysis of variation of lower order harmonics with modulating index for FHI-PWM: (a) Phase voltage, (b) Adjecent Line voltage, (c) Alternate Line Voltage

From the above simulation FFT analysis it can be observed that as modulating index increases from 0.05 to 1, the magnitude of lower order harmonics of all the three voltages, decreases in both the control techniques. However, as the modulating index goes beyond 1 i.e. 1.05 the magnitude of lower order harmonics increases drastically in PWM. In FHI-PWM, even though the modulating index is 1.05, there is no hazardous increment in the magnitude of lower order harmonics. Thus, it is possible to get enhanced output from the inverter by over modulating it without considerable injection of lower order harmonics using FHI-PWM technique.

The experimental results and their FFT analysis is carried out with the help of MATLAB/Simulink software. The sample values of the saved waveforms are imported in MALTAB work space and then using FFT block of powergui unit results are generated.With the help of FFT spectrums of all three voltages, here also the lower order harmonics in the inverter are compared for modulation index of 1.05 for both control technique. Bar charts are developed using Microsoft Excel. Fig. (8) shows the comparison for all three voltages.



(a)



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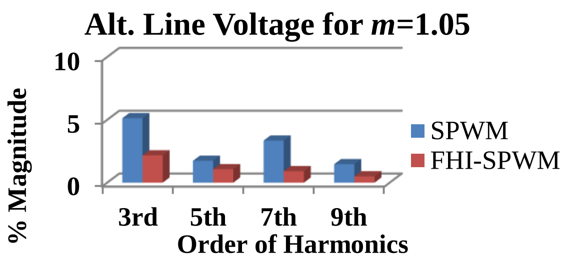

(c)

Figure 9: Comparative FFT analysis of lower order harmonics for *m*=1.05: (a) Phase voltage, (b) Adjecent Line voltage, (c) Alternate Line Voltage

Table III : Voltage %THD comparison for modulation index of 1.05

Voltage	**Simulation**		**Hardware**	
	PWM	**FHI-PWM**	**PWM**	**FHIPWM**
V_{Ph}	71.02	70.05	80.17	69.85
$V_L(adj.)$	103.37	102.94	98.59	100.84
$V_L(alt.)$	53.77	52.18	59.47	53.82

On the basis of same hardware results %THD of all the three voltages are compared for both PWM and FHI-PWM at modulation index of 1.05. Following Table 2 shows the %THD comparison mentioned above.

From the hardware FFT analysis it can be observed that in PWM the lower order harmonics and % THD of all three voltages are increased as modulating index goes beyond 1 i.e.

1.05. In FHI-PWM technique, these lower order harmonics and % THD have less effect of over modulation especially for phase and alternate line voltage as compared to PWM technique.

CONCLUSION

The over-modulation in PWM technique leads to increase the lower order harmonics in the inverter output. On the other hand, over-modulation in FHI-PWM not only improves the fundamental output voltage but also reduces the lower order harmonics and % THD to give better performance. Therefore, the fifth harmonic PWM gives better utilization of the input DC supply voltage than PWM. The injected fifth-harmonic component in the modulated signal voltages cancels out in the legs and does not appear in the phase output voltages. Also it is observed that alternate line voltage is better results than the phase and adjacent voltage.THD and lower order harmonics are less compared to phase and adjacent line voltage. If the motor winding connection is made as per alternate voltage as a phase voltage gives better power utilization and less core lower losses in the five-phase induction motor.

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