Analysis & Hardware Implementation Of Three-Phase Voltage Source Inverter

Prachi S. Dharmadhikari
M-Tech Student: Electrical Engg.Department
R.C.O.E.M,
Nagpur (India)

Gaurav N. Goyal
Asst. Prof : Electrical Engg. Department
R.C.O.E.M,
Nagpur (India)

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Abstract

With advances in solid-state power electronic devices and microprocessors, various pulse-width-modulation (PWM) techniques have been developed for industrial applications. For example, PWM-based three-phase voltage source inverters (VSI) convert DC power to AC power with variable voltage magnitude and variable frequency. This paper discusses three PWM techniques: the sinusoidal PWM (SPWM) technique, third-harmonic-injection PWM (THIPWM) technique & Digital PWM (DPWM) technique along with the analysis of Sensor less close-loop vector control of Induction motor drive. These PWM methods are compared by discussing their ease of implementation and by analyzing the output harmonic spectra of various output voltages and their total harmonic distortion (THD). The simulation results show that THIPWM techniques have lower total harmonic distortion than the SPWM & DPWM techniques & hardware implementation scheme for SPWM Inverter is discussed. The simulation results for Sensor less vector control are also discussed.

Keywords: SPWM Inverter; Sensor less Indirect vector control; Third harmonic injection; Three-Phase

1. Introduction

Pulse Width Modulated (PWM) voltage source inverters (VSI's) are widely utilized in ac motor drive application. Many PWM-VSI drives employ carrier based PWM methods due to fixed-switching frequency, low ripple current & well-defined harmonic spectrum characteristics. But a pulse width modulated inverter employing pure sinusoidal modulation cannot supply sufficient voltage to enable a standard motor to operate at rated power and rated speed. Sufficient voltage can be obtained from the inverter by over modulating, but this produces distortion of the output waveform [1]-[2]. In recent past, Third-Harmonic injection Pulse Width Modulation (THIPWM) switching technique is developed and widely used for three phase PWM inverter and the multilevel inverters [3]. It has been generally reported that third-harmonic injected modulation strategies offer superior performance compared to regular sampled pulse width modulation, in terms of reduced harmonic current ripple, optimized switching sequence and increased voltage transfer ratios. The voltage can be generally increased by harmonic suppression for the rectifiers as well as inverters. This can be mainly done by injecting the third harmonic component with fundamental in balanced three phase loads. At present, induction motors are the dominant drives in various industries. In recent years, demand for power converters that operate in high switching speed, low voltage with high power efficiency has become very high [4]- [7].

The aim of this paper is to develop a vector controlled induction motor drive operating without a speed or position sensor but having a dynamic performance comparable to a sensored vector drive. Vector control of induction motor is based upon the field-oriented co-ordinates aligned in the direction of the rotor m.m.f. However, there is no direct means of measuring the rotor flux linkage position Ψ and therefore an observer is needed to estimate Ψ for the implementation of sensorless vector control. With the help of synchronous reference frame model the indirect field oriented vector control, which is very popular and convenient method in real time implementation was developed [8]-[11].

2. General Theory of Voltage Source Inverter

Voltage source inverters as the name indicate, it receives dc voltage at one side and convert it to ac voltage on other side. According to the type of ac output waveform, these topologies can be considered as voltage source inverters (VSIs), where the independently controlled ac output is a voltage waveform. The ac voltage and the frequency may be variable or constant depending on the application. A voltage fed inverter should have a stiff voltage source at the input i.e. its Thevenin impedance should be ideally zero. A large capacitor can be connected at the input if the source is not stiff.

Three phase bridge inverter are widely used for ac motor drives and general purpose ac supplies. Fig 1 shows the inverter circuit suppling a star connected load. The circuit consist of three half bridge , which are mutually phase shifted by 2π/3 angle to generate the three phase voltage waves.

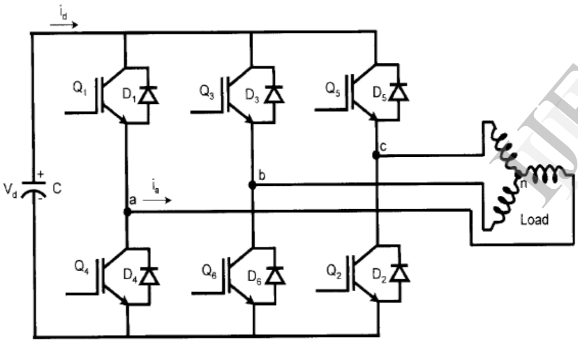


Fig 1: Circuit configuration of VSI.

The three phase bridge inverter is basically a six step bridge inverter. A step means firing of next SCR in the sequence. Thus in a cycle (360°), firing of six SCRs in a particular sequence forms six steps. Therefore, each firing is delayed by 60° from earlier firing. It means that the SCRs are fired at regular interval of 60º in a particular sequence to synthesize three phase voltage at the output terminals. The diodes used in the circuit are feedback diodes. The capacitor at input terminals helps to maintain constant dc supply voltage to inverter. This capacitor also helps to suppress harmonics resulting from inverter operation and prevent them from reaching to DC source. The three phase load connected at output terminals a, b, c is assumed to be a star or delta connected purely resistive load.

3. Different Pulse-Width Modulation Techniques

Up to date, due to the improvement of fast-switching power semiconductor devices and machine control algorithm, more precise PWM (Pulse Width Modulation) method finds particularly growing interest. The used PWM techniques are:

1 Sinusoidal pulse width modulation (SPWM)
2. Third Harmonic Injection pulse width modulation (THIPWM)
3. Digital pulse width modulation (DPWM)
4. Sensorless Indirect Vector Control of Induction motor drive

3.1 Sinusoidal Pulse Width Modulation

The sinusoidal pulse-width modulation (SPWM) technique produces a sinusoidal waveform by filtering an output pulse waveform with varying width. A high switching frequency leads to a better filtered sinusoidal output waveform. The variations in the amplitude and frequency of the reference voltage change the pulse-width patterns of the output voltage but keep the sinusoidal modulation. As shown in Figure 2, a low-frequency sinusoidal modulating waveform is compared with a high-frequency triangular waveform, which is called the carrier waveform. The switching state is changed when the sine waveform intersects the triangular waveform. The crossing positions determine the variable switching times between states.

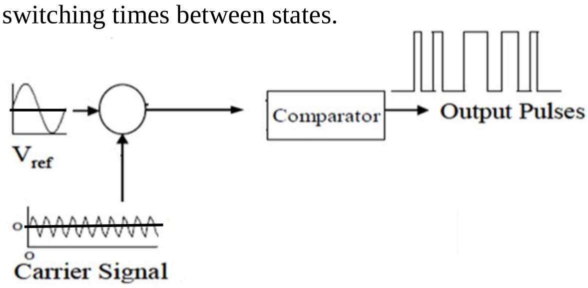


Fig 2: Block diagram for generation of SPWM pulses

The gating signals can be generated using unidirectional triangular carrier wave as shown in the figure 3. But a pulse width modulated inverter employing pure sinusoidal modulation cannot supply sufficient voltage to enable a standard motor to operate at rated power and rated speed. Sufficient voltage can be obtained from the inverter by over modulating, but this produces distortion of the output waveform. The linear output range of SPWM is restricted to 0.785 compared with six step inverter. The non-linear region operation (over-modulation) is leading to large amounts of sub carrier frequency harmonic currents, reduction in fundamental voltage gain and switching device gate pulse dropping.

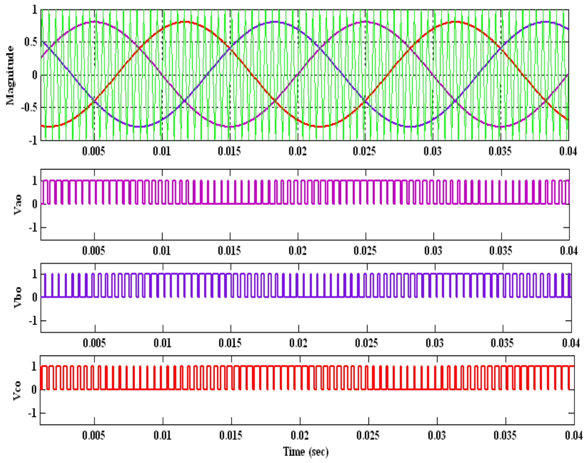


Fig 3: Carrier & Reference Waveform along with the pulses of Sinusoidal Pulse Width Modulation

3.2 Third-Harmonic Injection Pulse Width Modulation

The third – harmonic PWM is similar to the selected harmonic injection method & it is implemented in the same manner as sinusoidal PWM. The difference is that the reference ac waveform is not sinusoidal but consists of both a fundamental component and a third-harmonic component. As a result, the peak-to-peak amplitude of the resulting reference function does not exceed the DC supply voltage V_s, but the fundamental component is higher than the available supply V_s. The block diagram for Third Harmonic Injection is shown below in figure 4.

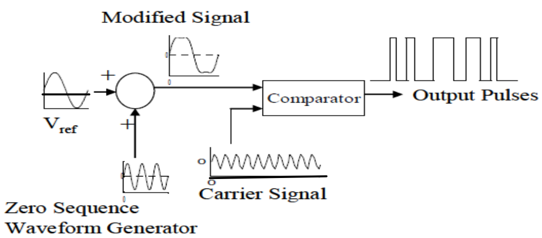


Fig 4: Block diagram for generation of THIPWM pulses

The reference voltage V_{ref} is added with signal having frequency three times of fundamental frequency and the magnitude is 1/6th of the fundamental amplitude. The resultant is then passed through comparator which compares the modified signal with the carrier signal of frequency 2 KHz. The presence of exactly the same third-harmonic component in each phase results in an effective cancellation of the third harmonic component in the neutral terminal, and the line-to-neutral phase voltages are all sinusoidal with the peak amplitude.

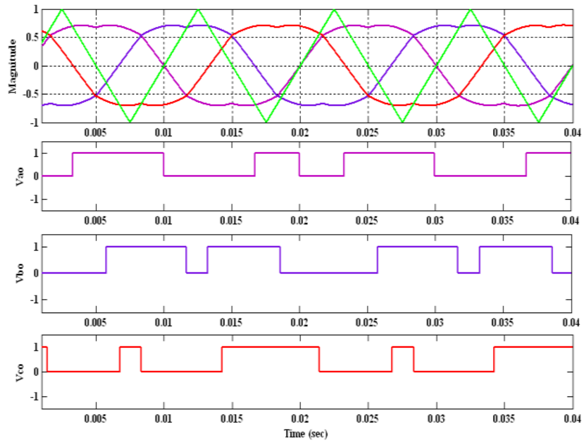


Fig 5: Carrier & Reference Waveform along with the pulses of Third Harmonic Injection Pulse Width Modulation

By injecting the third harmonic into the reference voltage signal, the fundamental of the phase voltage can be increased. The voltage can be increased by harmonic suppression for the rectifiers as well as inverters. This can be mainly done by injecting the third harmonic.

3.3 Digital Pulse Width Modulation

In recent years, the interest on digital control for switching power converters has grown considerably. In order to reduce limit cycle oscillations, high resolution digital pulse width modular (DPWM) is mandatory for the system implementation especially for the applications with high switching frequency and tight output regulation.

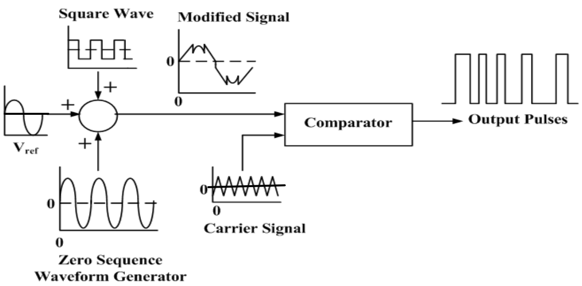


Fig 6: Block diagram for generation of DPWM pulses

DPWM scheme is used to improve resolution while keeping relative low cost. For the method of dithering DPWM, it increases the resolution by averaging several adjacent switching periods' duty cycle values;

hence, a large magnitude output ripple is resulted although the limit-cycle oscillation could be reduced.

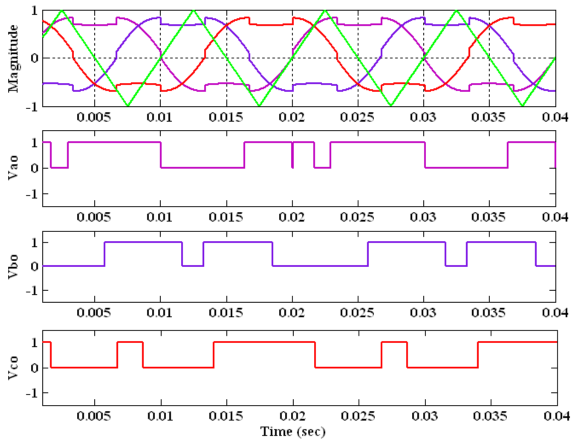


Fig 7: Carrier & Reference Waveform along with the pulses of Third Harmonic Injection Pulse Width Modulation

3.4 Sensor less Indirect Vector Control of Induction Motor Drive

Sensor less vector control induction motor drive essentially means vector control without any speed sensor. A speed signal is also required in indirect vector control in the whole speed range and in direct vector control for the low speed range, including the zero speed start up operation. Speed encoders undesirable in a drive because it adds cost and reliability problems, besides the need for a shaft extension and mounting arrangement. Controlled induction motor drives without mechanical speed sensors at the motor shaft have the attractions of low cost and high reliability. To reduce total hardware complexity, costs and to increase mechanical robustness, it is desirable to eliminate speed and position sensors in vector-controlled drives. To replace the sensor the information on the rotor speed is extracted from measured stator voltages and currents at the motor terminals. The operation of speed controlled ac drives without mechanical speed or position sensors requires the estimation of internal state variables of the machine. The assessment is based exclusively on measured terminal voltages and currents. Speed estimation is an issue of particular interest with induction motor drives where the mechanical speed of the rotor is generally different from the speed of the revolving magnetic field. The schematic diagram of control strategy of induction motor with sensorless control is shown in Fig 8.

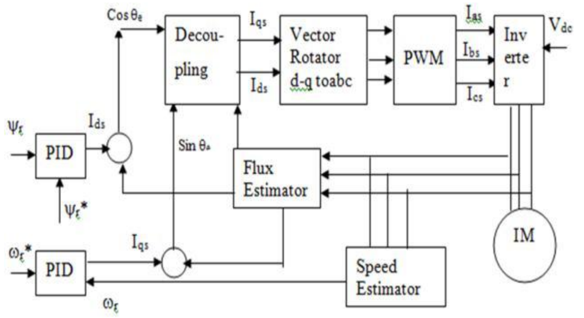


Fig 8: Block diagram of Sensorless control of Induction motor

The inherent coupling of motor is eliminated by controlling the motor by vector control, like in the case of as a separately excited motor. The inverter provides switching pulses for the control of the motor. The flux and speed estimators are used to estimate the flux and speed respectively. These signals then compared with reference values and controlled by using the PI controller. The controller output is give to the decoupler which in turn is connected to vector rotator, which converts 2-phase to 3- phase quantities and these signals are given to PWM converter. The dynamic model for the three-phase induction machine in a rotating reference frame can be described by the following equations:

$$\left.\begin{aligned} \varphi_{qs} &= L_s i_{qs} + L_m i_{qr} \\ \varphi_{ds} &= L_s i_{ds} + L_m i_{dr} \\ \varphi_{qr} &= L_r i_{qr} + L_m i_{qs} \\ \varphi_{dr} &= L_r i_{dr} + L_m i_{ds} \end{aligned}\right\} \text{--------} \quad (1)$$

$$\left.\begin{aligned} \varphi_{qm} &= L_m\left(i_{qs} + i_{qr}\right) \\ \varphi_{dm} &= L_m\left(i_{ds} + i_{dr}\right) \end{aligned}\right\} \text{--------} \quad (2)$$

From equation (1) & (2) we get,

$$\left.\begin{aligned} v_{ds} &= R_s i_{ds} + \frac{d}{dt}\varphi_{ds} \\ v_{qs} &= R_s i_{qs} + \frac{d}{dt}\varphi_{qs} \\ v_{dr} &= R_r i_{dr} + \omega_r \varphi_{qr} + \frac{d}{dt}\varphi_{dr} \\ v_{qr} &= R_r i_{qr} - \omega_r \varphi_{dr} + \frac{d}{dt}\varphi_{qr} \end{aligned}\right\} \text{--------} \quad (3)$$

From stator voltage equation (3)

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} \text{ --------} \quad (4)$$

With equation (1) & (2) the equation (4) will be

$$v_{ds} = R_s i_{ds} + L_{ls}\frac{d}{dt}(i_{ds}) + \frac{d}{dt}\varphi_{dm} \text{ --------} \quad (5)$$

Equation (1) is

$$\varphi_{dr} = L_r i_{dr} + L_m i_{ds} -------- (6)$$

With equation (1) the equation (6) is modified as

$$\varphi_{dr} = \frac{L_r}{L_m}\varphi_{dm} - L_{lr} i_{ds} -------- (7)$$

Rearranging the equation (7)

$$\varphi_{dm} = \frac{L_m \varphi_{dr} + L_{lr} L_m i_{ds}}{L_r} -------- (8)$$

Substituting equation (8) in (5)

$$v_{ds} = \frac{L_m}{L_r}\frac{d}{dt}\varphi_{dr} + (R_s + \sigma S L_s) i_{ds} ------- (9)$$

where $\sigma = 1 - \frac{L_m^2}{L_r L_s}$ is the linkage coefficient,

$$L_{ls} = L_s - L_m \ \& \ L_{lr} = L_r - L_m$$

Rearranging the above equation

$$\frac{d}{dt}\varphi_{dr} = \frac{L_r}{L_m}[v_{ds} - (R_s + \sigma S L_s) i_{ds}] ------- (10)$$

Similarly,

$$\frac{d}{dt}\varphi_{qr} = \frac{L_r}{L_m}[v_{qs} - (R_s + \sigma S L_s) i_{ds}] ------- (11)$$

The PI speed controller is designed in order to stabilize the closed-loop sensor less speed control. Closed-loop speed control with slip regulation adds some performance improvement to open-loop volts/Hz control. Here, the motor speed is compared with the command speed, & the error generates the slip frequency (ω_{sl}^*) command through a P-I controller & limiter. The slip is added to the feedback speed to generate the frequency. Because slip is proportional to torque at constant air gap flux, the scheme is considered as torque control within a speed control loop.

4. Simulation Results

The simulation of Sensor less control of induction Motor is done by using MATLAB-SIMULINK.

Table 1. Inverter parameters

DC Bus Voltage	800 V
Carrier frequency	2 kHz

Table 2. Induction motor parameters

Rated Power	2.2 KW
Rated Voltage	415 V
Rated Frequency	50Hz
Number of Pole pairs	4
Stator resistance (R_s)	11.1 Ω
Rotor resistance (R_r')	2.2605 Ω
Stator Inductance (Lls)	0.018189 H
Mutual Inductance (L_m)	0.71469 H

4.1 Simulation results for SPWM

In the fig.9 (a) the current and the voltage waveforms obtained from the inverter when fed with the SPWM pulses are shown.

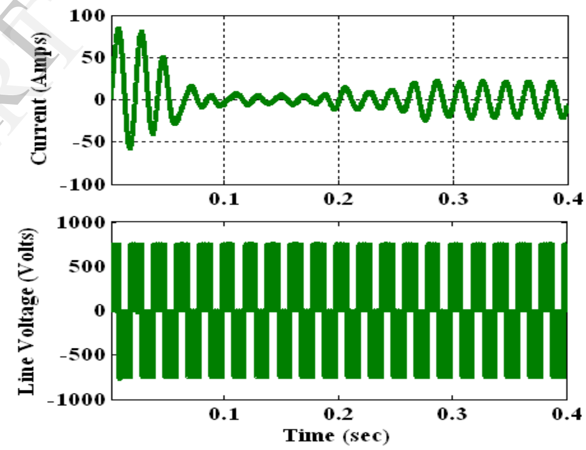


Fig.9 (a) Machine Line voltage and current with V_{DC}= 800 V for SPWM

The current waveform contains some harmonic distortion in the form of spikes i.e. overshooting of the magnitude. The frequency of both current and voltage is 50Hz that can be observed from the waveform.

Fig. 9(b) shows the waveforms of torque & speed of an Induction motor varied for 25N-m to 50N-m for t= 0.18 & 0.25 sec respectively.

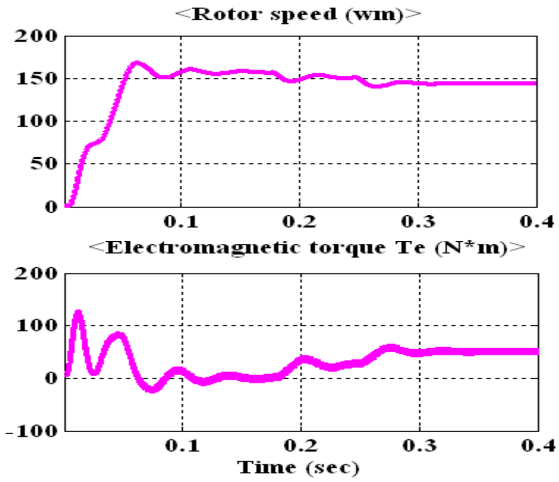


Fig. 9 (b) shows speed & Electromagnetic Torque of SPWM

4.2 Simulation results for THIPWM

In the fig 10 (a) the current and the voltage waveform of the inverter fed induction motor drive is shown:-

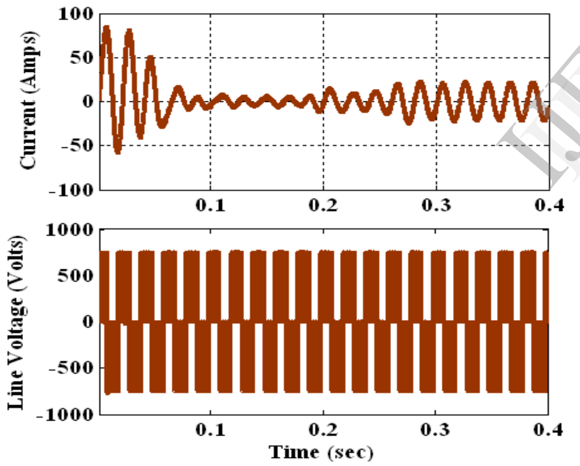


Fig.10 (a) Current and Voltage waveforms of THIPWM

The corresponding torque generated by motor (electromagnetic torque) and speed of induction motor are shown in Fig. 10(b).

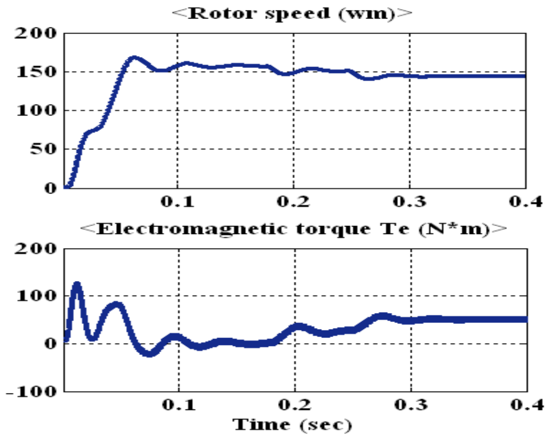


Fig. 10 (b) shows speed & Electromagnetic Torque of THIPWM

4.3 Simulation results for DPWM

In the fig 11 (a) the current and the voltage waveform of the inverter fed induction motor drive is shown:-

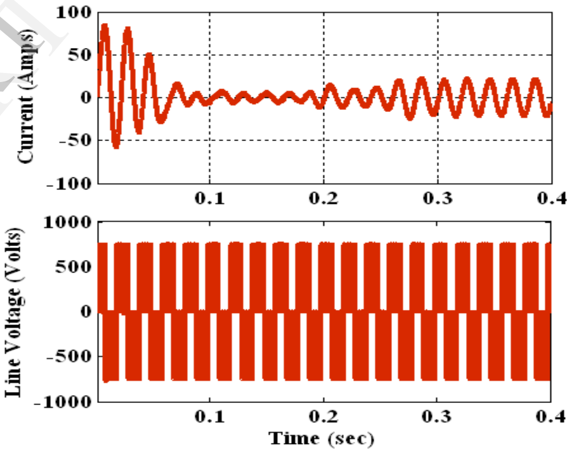


Fig.11 (a) Current and Voltage waveforms of DPWM

The corresponding torque generated by motor (electromagnetic torque) and speed of induction motor are shown in Fig. 11 (b)

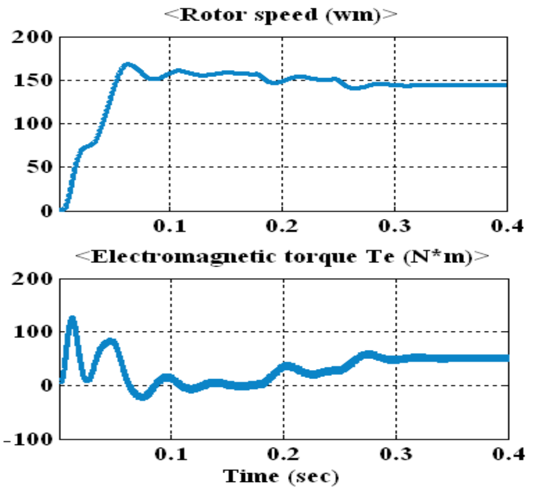


Fig. 11 (b) shows speed & Electromagnetic Torque of DPWM

4.4 Simulation results for Sensor less Control of Induction Motor

The simulation of Sensor less control of induction motor is done by using MATLAB-SIMULINK. The results for different cases are given below.

Case-1: No-Load Condition

Reference speed = 100 rad/sec

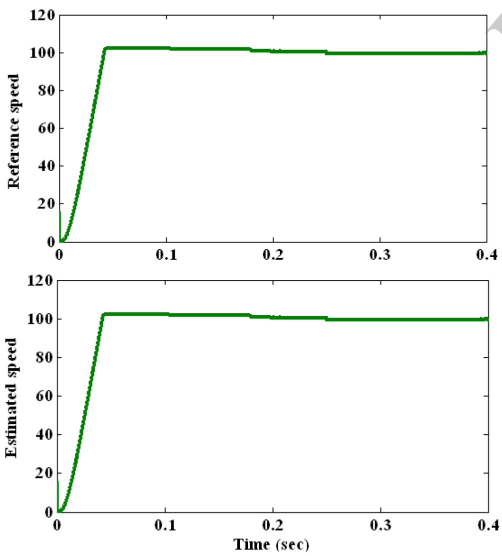


Fig 12. Shows that the reference speed of induction motor and estimated speed

Fig 13 (a) Show direct and quadrature axes currents (I_{ds} & I_{qs}).

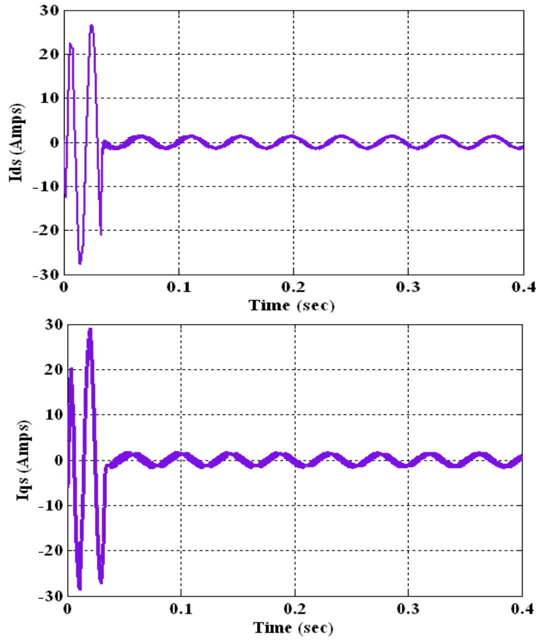


Fig 13(a) Direct and Quadrature axes currents (I_{ds} & I_{qs})

From the graph it is observed that both currents are displaced by 90^0. Hence the coupling effect can be eliminated.

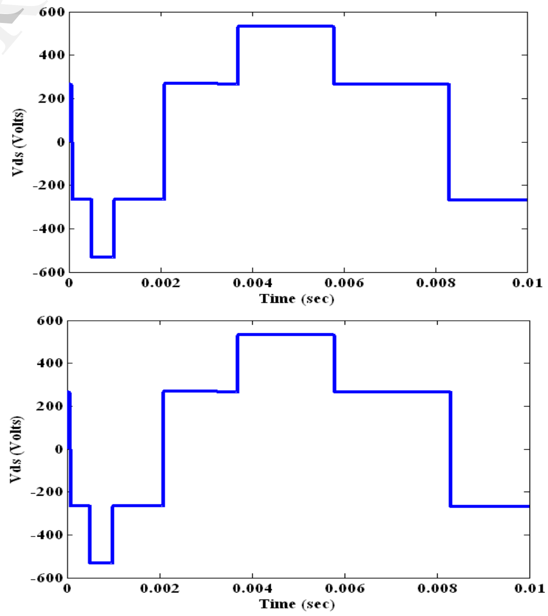


Fig 13(b) Direct and Quadrature axes voltages (V_{ds} &V_{qs})

Fig 14 Shows the no load line currents and torque waveforms.

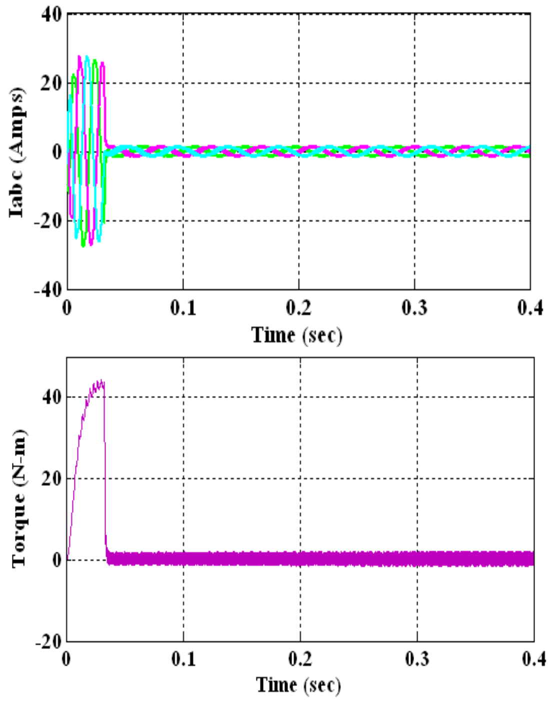
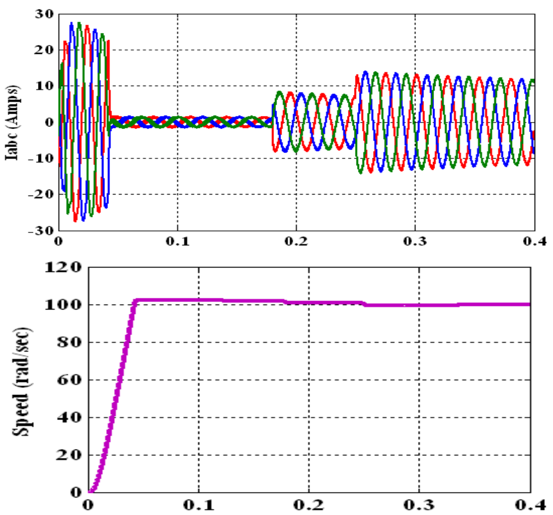


Fig 14 (a) Line currents in Amps (b) Torque in N-m on no load

It can be seen that at starting the values of currents and torque will be high. The motor reaches to its final steady state position within 0.05 sec. Hence it has fast dynamic response.

Case-2: Variation in Load

Reference speed = 100 rad/sec; Load torque of 25 N-m to 50N-m is applied at t=0.18 & 0.25 sec.



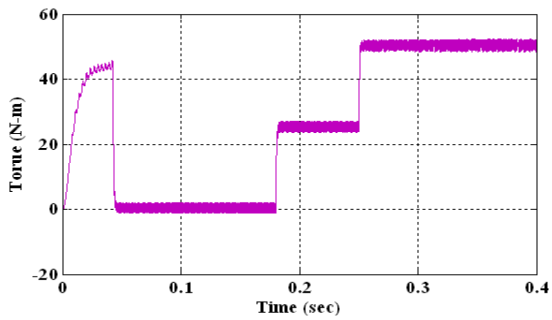


Fig 15 (a) Line currents, (b) speed and (c) torque waveforms under load condition.

First the motor is started under no load and at t = 0.18 sec a load of 25 N-m is applied. It can seen that at 0.18 sec, the values of currents & torque will increase to meet the load demand and at the same time speed of motor slightly falls. Similarly, at 0.25 sec the same observations can be done.

5. Hardware Results for SPWM Inverter

Experiments were carried using SPWM as resistive load. The frequency of the inverter is 1 KHz. The MOSFET IRF 840 is used as switching devices. The dead time in the inverter is as 25μs.

Table 3. Lab Model (Hardware Details)

Switching Frequency	1KHz
MOSFET (IRF840)	8A,500V
DC Link Voltage	10V

A. Carrier Waveform Generation

The carrier waveform obtained from the operational amplifier circuit is shown in the fig 16. The frequency and the amplitude of the triangular wave are set as 1 KHz and 8V (peak to peak) respectively. The same carrier signal is used for the pulse generation in SPWM.

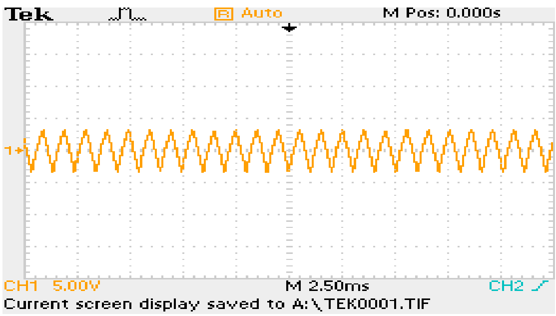


Fig. 16 Carrier waveform of 1 KHz frequency

B. Three-Phase Sine Wave Generation

Three-Phase sine waves are generated which are 120^0 displaced from each other as shown in figure 17. Its peak-peak voltage is 3.20V.

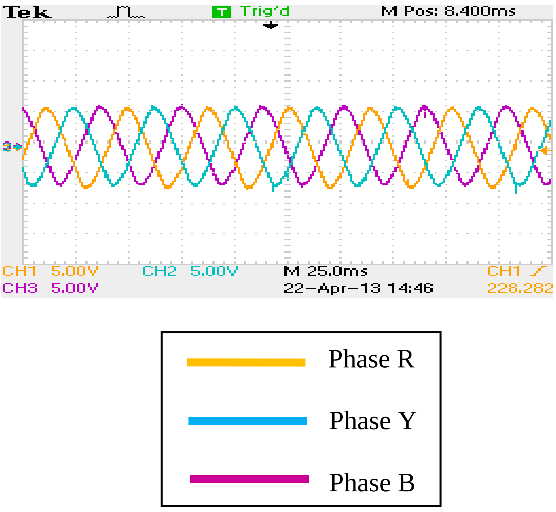


Fig. 17 Three-phase Sine wave generation of 50Hz frequency

C. SPWM Pulses

The gating signals for turning on the switches are generated by comparing a high frequency carrier signal with a sinusoidal reference signal of desired frequency and it is shown in fig 18. It is generated by comparing 1 KHz carrier wave and 50 Hz referencesinewave.

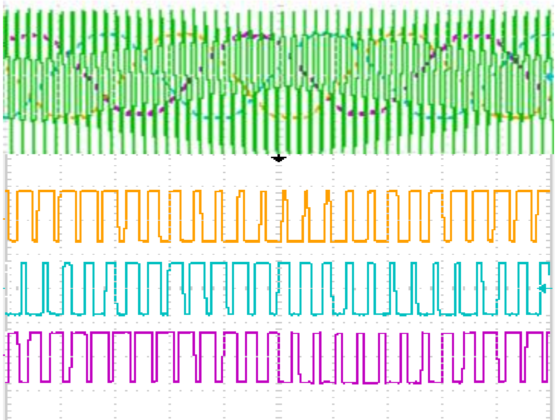


Fig. 18 SPWM Pulses for Phases R, Y & B respectively

D. Line voltage waveform for SPWM

In the figure 19 the voltage waveform obtained from the inverter when fed with the SPWM pulses is shown. The maximum value of Line voltage = 10V

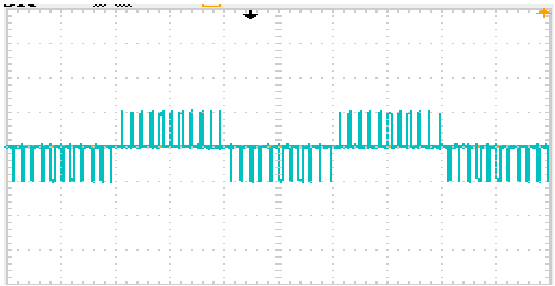


Fig. 19 Line voltage waveform (V_{ab})

Table 4 shows the values of the THD for output voltage for SPWM, THIPWM & DPWM techniques.

Table 4. Total Harmonic Distortion for Voltage at different Modulation index for SPWM, THIPWM & DPWM techniques (Carrier frequency= 2 kHz)

Modulation Index	Voltage (THD value)		
	SPWM	THIPWM	DPWM
M=1	68.3	54.2	59.6
M=0.8	91.5	78.5	80.3
M=0.6	120.4	109.6	110.8

It is been observed that the THD for THIPWM technique is better than the SPWM & DPWM

6. Conclusion

The Voltage source inverter operation with SPWM, THIPWM & DPWM is simulated and their performance has been presented. The effectiveness of THIPWM technique in this operation improves the inverter output rms voltage for a given DC bus voltages as compare to SPWM & DPWM. Thus it gives effective utilization of the inverter and enhancement of rms content of the output voltage. From the simulation results of Indirect vector control of Induction motor drive, it can be observed that, in steady state there are ripples in torque wave and also the starting current is high. The main results obtained from the Simulation, the following observations are made.

i) The transient response of the drive is fast, i.e. we are attaining steady state very quickly.

ii) The speed response is same for both vector control and Sensor less control.
iii) By using Indirect vector control, we are estimating the speed, which is same as that of reference speed of induction motor.
Thus by using sensor less control we can get the same results as that of vector control without shaft encoder. Hence by using this proposed technique, we can reduce the cost of drive i.e. shaft encoder's cost, we can also increase the ruggedness of the motor as well as fast dynamic response can be achieved.

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References

[1] Mr. JOBY JOSE, Prof. G.N.GOYAL and Dr. M.V.AWARE "Improved Inverter Utilization Using Third Harmonic Injection".
[2] Srinivasa Rao Maturu* and Avinash VujjiDing, "SVPWM Based Speed Control of Induction Motor Drive with Using V/F Control Based 3-Level Inverter" VSRD-IJEECE, Vol. 2 (7), 2012, 421- 437
[3] Prof. G.N.GOYAL and Dr. M.V.AWARE "A Comparative Performance of Six-Phase Nine Switch Inverter Operation with SPWM and SVPWM"

[4] Yang Qiu, Jian Li, Ming Xu, Dong S. Ha, Fred C. Lee "Proposed DPWM Scheme with Improved Resolution for Switching Power Converters" at Center for Power Electronics Systems Virginia Polytechnic Institute and State University Blacksburg, VA 24061 USA
[5] Yunxiang Wu, Mohsin A. Shafi, Andrew M. Knight and Richard A. McMahon "Comparison of the Effects of Continuous and Discontinuous PWM Schemes on Power Losses of Voltage-Sourced Inverters for Induction Motor Drives", IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 26, NO. 1, JANUARY 2011
[6] Cristian Aghion, Mihai Lucanu, Ovidiu Ursaru "Gh. ASACHI" Technical University of Iasi Faculty of Electronics, Telecommunications and Information Technology, "DPWM-S3 Software Control for Three-phase Inverters" .
[7] Lu-Sheng Ge, Zong-Xiang Chen, Zhi-Jie Chen and Yan-Fei Liu1, (Senior Member, IEEE) "Design and Implementation of A High Resolution DPWM Based on A Low-Cost FPGA"
[8] Pardasani Hitendra K. Arora Kapildev N. "Simulation of Three Level Inverter Using Sinusoidal Pulse Width Modulation Technique by MATLAB," National Conference on Recent Trends in Engineering & Technology
[9] Mahrous E. Ahmed & Saad Mekhilef "Three-Phase Three-Level Nine Switches Inverter Employing Space Vector Modulation".
[10]Sharad.S.Patil, R.M.Holmukhe , P.S.Chaudhari "Steady state analysis of PWM inverter fed cage induction motor drive" Proceedings of International Conference on Energy Optimization and Control (ICEOC-2010) December 28 - 30.2010. Aurangabad, Maharashtra, India
[11] Bimal K.Bose 'Modern Power Electronics and AC Drives' Pearson Education, Singapore.2003
[12] M.H.Rashid, 'Power Electronics: Circuits, Devices and Applications', Pearson Education, 2004.