Simulation and Analysis of SVPWM Based 2-Level and 3-Level Inverters for Direct Torque of Induction Motor

M. Lakshmi Swarupa, G. Tulasi Ram Das and P.V. Raj Gopal

Associate Processor, MRECW Engg College, Director of Academic & Planning, AGM, BHEL R&D

Abstract

In this paper, new scheme of direct torque control of induction motor for electric vehicles is proposed and the results of an investigation into suitable torque control schemes are also presented. The electric vehicle drive consists of rewound induction motors and a three-level IGBT inverter. The schemes investigated are Field Oriented Control, Direct Torque Control (DTC), and DTC using Space Vector Modulation. The results of Matlab - Simulink simulations and a comparison between the control schemes are presented. It is found that the DTC using Space Vector Modulation scheme is best for this application.

For industrial applications, variation in the output voltage of inverter is often required.

This is mainly for
- Overcoming the variation in dc input voltage.
- Maintaining the v/f ratio of induction motor constant.
- Compensating for regulation of inverters.

Here space vector control for voltage control of multi level inverters which are gaining lot of importance in industry.

This paper is to acquire the knowledge on *space vector control of PWM*, its various advantages and to have complete idea on the operation of *Multi level inverters*, then employ space vector approach to PWM to control the output voltage of multi level inverters. This paper presents the implementation of a high-performance direct torque control (DTC) of induction machines drive.

DTC has two major problems, namely, high torque ripple and variable switching frequency. DTC is a control method that embeds a motor and inverter together and controls them together in an optimal manner. The new torque and flux controllers with constant switching frequency and low torque

and flux ripples for direct torque control induction machine drives are presented. The core of these proposed controllers is based on the comparison between the compensated error signals with high frequency triangular waveforms, thus does not require complex calculation to generate the inverter switching signals. The controllers are therefore implemented using analog and/or digital circuits. Modeling and simulation of the new controllers are presented and the results show that the torque and flux ripples are reduced significantly. In order to solve these problems, this paper proposed a pair of torque and flux controllers. The simulation of the proposed controllers applied to the DTC drive is presented in MATLAB/SIMULINK. The simulation results are then verified.

Index terms: DTC, Two-Level, Three-Level, SVM-PWM, Simulink.

Introduction

Various speed control techniques implemented by modern-age VFD are mainly classified in the following three categories:

- Scalar Control (V/f Control)
- Vector Control (Indirect Torque Control)
- Direct Torque Control (DTC)

- **Scalar Control**

In this type of control, the motor is fed with variable frequency signals generated by the PWM control from an inverter using the feature rich PIC micro microcontroller. Here, the V/f ratio is maintained constant in order to get constant torque over the entire operating range. Since only magnitudes of the input variables – frequency and voltage – are controlled, this is known as "scalar control". Generally, the drives with such a control are without any feedback devices (open loop control). Hence, a control of this type offers low cost and is an easy to implement solution. In such controls, very little knowledge of the motor is required for frequency control.

Thus, this control is widely used. A disadvantage of such a control is that the torque developed is load dependent as it is not controlled directly. Also, the transient response of such a control is not fast due to the predefined switching pattern of the inverter. However, if there is a continuous block to the rotor rotation, it will lead to heating of the motor regardless of implementation of the over current control loop. By adding a speed/position sensor, the problem relating to the blocked rotor and the load dependent speed can be overcome. However, this will add to the system cost, size and complexity. There are a number of ways to implement scalar control. The popular schemes are described in the following sections.

- **Vector Control**

This control is also known as the "field oriented control", "flux oriented control" or "indirect torque control". Using field orientation (Clarke-Park transformation), three-phase current vectors are converted to a two-dimensional rotating reference frame (d-

q) from a three-dimensional stationary reference frame. The "d" component represents the flux producing component of the stator current and the "q" component represents the torque producing component. These two decoupled components can be independently controlled by passing though separate PI controllers.

The outputs of the PI controllers are transformed back to the three-dimensional stationary reference plane using the inverse of the Clarke-Park transformation. The corresponding switching pattern is pulse width modulated and implemented using the SVM.

This control simulates a separately exited DC motor model, which provides an excellent torque-speed curve. The transformation from the stationary reference frame to the rotating reference frame is done and controlled (stator flux linkage, rotor flux linkage or magnetizing flux linkage). In general, there exists three possibilities for such selection and hence, three different vector controls. They are:

- Stator flux oriented control
- Rotor flux oriented control
- Magnetizing flux oriented control

As the torque producing component in this type of control is controlled only after transformation is done and is not the main input reference, such control is known as "indirect torque control".

The most challenging and ultimately, the limiting feature of the field orientation, is the method whereby the flux angle is measured or estimated. Depending on the method of measurement, the vector control is divided into two subcategories: direct and indirect vector control. In direct vector control, the flux measurement is done by using the flux sensing coils or the Hall devices. This adds to additional hardware cost and in addition, measurement is not highly accurate. Therefore, this method is not a very good control technique.

The most common method is indirect vector control. In this method, the flux angle is not measured directly, but is estimated from the equivalent circuit model and from measurements of the rotor speed, the stator current and the voltage. One common technique for estimating the rotor flux is based on the slip relation. This requires the measurement of the rotor position and the stator current. With current and position sensors, this method performs reasonably well over the entire speed range.

The most high-performance VFDs in operation today employ indirect field orientation based on the slip relation. The main disadvantage of this method is the need of the rotor position information using the shaft mounted encoder. This means additional wiring and component cost. This increases the size of the motor. When the drive and the motor are far apart, the additional wiring poses a challenge. To overcome the sensor/encoder problem, today's main research focus is in the area of a sensorless approach. The advantages of the vector control are to better the torque response compared to the scalar control, full-load torque close to zero speed, accurate speed control and performance approaching DC drive, among others. But this requires a complex algorithm for speed calculation in real-time. Due to feedback devices, this control becomes costly compared to the scalar control.

- **Direct Torque Control (DTC)**

The difference between the traditional vector control and the DTC is that the DTC has no fixed switching pattern. The DTC switches the inverter according to the load needs. Due to elimination of the fixed switching pattern (characteristic of the vector and the scalar control), the DTC response is extremely fast during the instant load changes. Although the speed accuracy up to 0.5% is ensured with this complex technology, it eliminates the requirement of any feedback device. The heart of this technology is its adaptive motor model. This model is based on the mathematical expressions of basic motor theory. This model requires information about the various motor parameters, like stator resistance, mutual inductance, saturation co efficiency, etc.

The algorithm captures all these details at the start from the motor without rotating the motor. But rotating the motor for a few seconds helps in the tuning of the model. The better the tuning, the higher the accuracy of speed and torque control. With the DC bus voltage, the line currents and the present switch position as inputs, the model calculates actual flux and torque of the motor. These values are fed to two-level comparators of the torque and flux, respectively.

The output of these comparators is the torque and flux reference signals for the optimal switch selection table. Selected switch position is given to the inverter without any modulation, which means faster response time. The external speed set reference signal is decoded to generate the torque and flux reference. Thus, in the DTC, the motor torque and flux become direct controlled variables and hence, the name – Direct Torque Control.

The advantage of this technology is the fastest response time, elimination of feedback devices, reduced mechanical failure, performance nearly the same as the DC machine without feedback, etc. The disadvantage is due to the inherent hysteresis of the comparator, higher torque and flux ripple exist. Since switching is not done at a very high frequency, the low order harmonics increases.

It is believed that the DTC can be implemented using an Artificial Intelligence model instead of the model based on mathematical equations. This will help in better tuning of the model and less dependence on the motor parameters.

Introduction to DTC

In the past, AC drives were only used in small demanding applications, regardless the advantages of AC motors opposite to DC motors, since the high switching frequency inverters cost was rather competitive. With the developments in the power electronics area, the vector control methods, which use fast microprocessors and DSP's, made possible the use of induction motors in typically DC motors dominated areas, since the current components producing torque and flux are decoupled, achieving the system separately excited DC motor similar features.

The Direct Torque Control (DTC) method, developed by German and Japanese researchers [8], [3], allows direct and independent electromagnetic torque and flux control, selecting an optimal switching vector, making possible fast torque response, low inverter switching frequency and low harmonic losses.

Figure 1 shows the usual block diagram of a DTC controller. With DTC it is possible to obtain direct flux and electromagnetic torque control, indirect voltage and current control, sinusoidal current and flux, low torque ripple, superior torque dynamics and hysteresis band dependent inverter switching frequency [5], [2].
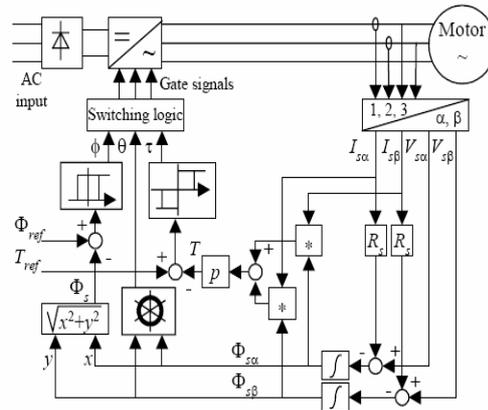

Figure 1: Block diagram of a DTC control system.

Among its main advantages are the absence of: coordinate transformation (which are usually necessary in most vector control drives), modulation specific block, and the absolute position determination. However, there are some problems during start up and at low speed values, like the difficulty in start up current control and high influence of the motor and the need of flux and speed estimators.

With the inclusion of a speed estimator in the system, it is possible to obtain gains in hardware complexity reduction and bigger mechanical endurance, making possible the operation in a hostile environment and decreasing the maintenance needs. Simultaneously the noise and motor-load inertia immunity are increased.

In this paper, it is introduced the work developed in simulation and experimentation associated to the implementation of a DTC based, Two-Level and Three Level inverters , of an asynchronous machine, in torque and speed modes.

Principle of operation of Direct Torque Control

In principle, the DTC method selects one of the inverter's six voltage vectors and two zero vectors in order to keep the stator flux and torque within a hysteresis band around the demand flux and torque magnitudes. The torque produced by the induction motor can be expressed as Equation (4),

$$T_{em} = \frac{3}{2} \frac{P}{Ls'} \frac{L_m}{L_r} \; \left| \overline{\lambda_r} \right| \left| \overline{\lambda_s} \right| . \sin \alpha$$

(4)

which shows the torque produced is dependent on the stator flux magnitude, rotor flux magnitude, and the phase angle between the stator and rotor flux vectors. The induction motor stator equation, (5),

$$\overline{V}_s = \frac{d\overline{\lambda}_s}{dt} - \overline{I}_s.r_s$$

(5)

can be approximated as Equation (6) over a short time period if the stator resistance is ignored.

$$\Delta\overline{\lambda}_s = \overline{V}_s.\Delta t$$

(6)

This means that the applied voltage vector as shown in Figure 2(b) determines the change in the stator flux vector as shown in figure 2(a). If a voltage vector is applied that changes the stator flux to increase the phase angle between the stator flux and rotor flux vectors, then the torque produced will increase.
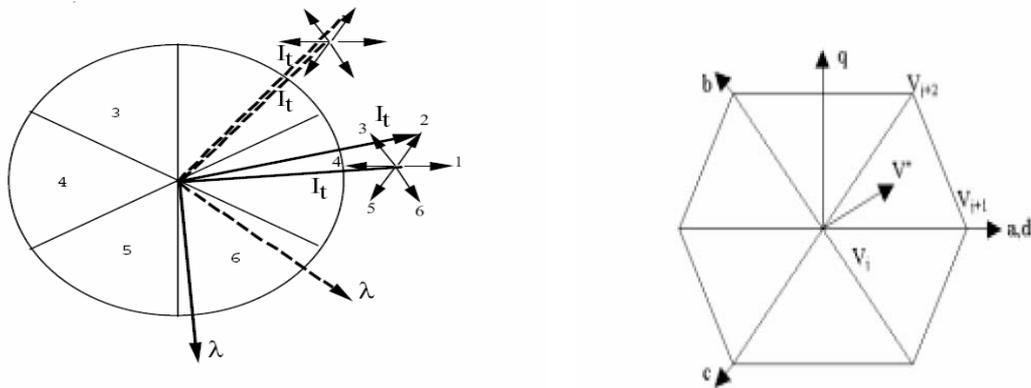
Figure 2(a): Torque change corresponding to the position of flux.

Figure 2(b): Direct Torque Control Operation (2-level)

Since a two-level inverter is only capable of producing six non-zero voltage vectors and two zero vectors, it is possible to create a table that determines the voltage vector to apply based on the position of the stator flux and the required changes in stator flux magnitude and torque. This is called the optimal vector selection table and is shown as Table 1 for thecae of a two level inverter. It is possible to expand the optimal vector selection table to include the larger number of voltage vectors produced by a three-level inverter.

TABLE 1: OPTIMAL VECTOR SELECTION TABLE
(2-LEVEL) SECTOR

		Sector					
$\Delta\lambda$	ΔT_{em}	1	2	3	4	5	6
↑	↑	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_0	V_0	V_0	V_0	V_0	V_0
	↓	V_6	V_1	V_2	V_3	V_4	V_5
↓	↑	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_0	V_0	V_0	V_0	V_0
	↓	V_5	V_6	V_1	V_2	V_3	V_4

The stator flux vector can be estimated using the stator voltage equation, (5), as given in Equation (7).

$$\overline{\lambda_s} = \int \left(\overline{V_s} - r_s \overline{I_s} \right) dt \qquad (7)$$

As shown in Figure 3, the estimated stator flux magnitude and torque output is compared to the demand values. A voltage vector is then selected that will drive the torque and flux towards the demanded values.
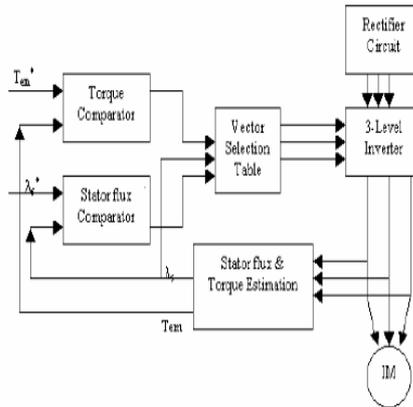
Figure 3: Direct Torque Control Block Diagram.

Direct torque control using space vector modulation
Based on instantaneous current and voltage measurements it is possible to calculate the voltage required to drive the current output torque and stator flux to the demanded values within a fixed time period.

This calculated voltage is then synthesized using Space Vector Modulation. The applied voltage and motor current can be used to estimate the instantaneous stator flux and output torque. From these the required change in output torque and stator flux in order to reach the demanded values by the end of the current switching period can becalculated. Equation (8) shows that a change in torque corresponds to a change in stator current. The voltage V, required to achieve that change in stator current can be

calculated knowing the back EMF of the motor. The back EMF can be calculated from the stator flux and current.

$$\Delta T_{em} = \frac{3}{2}\frac{P}{2}\left(\overline{\lambda_s} \; X \Delta \overline{I_s}\right)$$

(8)

$$\Delta T_{em} = \frac{3}{2}\frac{P}{2}\frac{\Delta t}{L_s'}\left(\overline{\lambda_s} \; X(V - E)\;\right)$$

(9)

$$\Delta\lambda_s = V.\Delta t$$

(10)

Comparison

Direct Torque Control was developed as an alternative to FOC that had been in use for a number of years.DTC has the advantage of not requiring speed or position encoders and uses voltage and current measurements only. It also has a faster dynamic response due to the absence of the PI current regulator. A disadvantage of DTC is its comparatively high current distortion and torque ripple. DTC using SVM is a different approach that involves a direct predictive calculation of the voltage required to be applied to the induction motor to change the stator flux and torque magnitudes to the demanded values. It combines the best features of the direct torque control schemes such as fast torque response, no fixed switching frequency. DTC using SVM was chosen as the torque control scheme in this electric vehicle application. From the above discussions, advantages and disadvantages of all the control schemes are summarized as follows:

Direct Torque control
Advantages
    (i) Fast torque response
    (ii) Relatively simple
    (iii)No speed or position encoder is required

    Disadvantages
    (i) High current distortion
    (ii) High torque ripple
    (iii)Switching frequency changes with motor speed.

DTC using Space Vector Modulation
Advantages
   (i) Fast torque response that is equivalent to standard direct torque control
    (ii) Low steady state torque ripple and current distortion that is equal to FOC
    (iii)Constant switching frequency
    (iv)Not as parameter sensitive as FOC
   (v) No speed or position encoder is required

Disadvantages
    (i) The control algorithm is very complex compared to other control schemes.
    (ii) It requires a relatively fast processor to implement at the desired switching frequency.

Conclusions

Three different control schemes have been evaluated for induction motor torque control in an electric vehicle application. All other direct torque control (either 2-level and 3-level) techniques exhibited improved transient torque response compared to standard rotor flux FOC. The disadvantage of these schemes is increased current distortion. Since high efficiency is one of the prime requirements for an electric vehicle drive and high current distortion results in increase motor losses, this is unacceptable. DTC using space vector modulation is an exception that exhibited fast torque response and low current distortion and torque ripple.
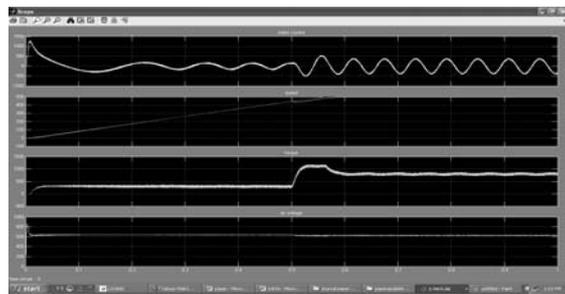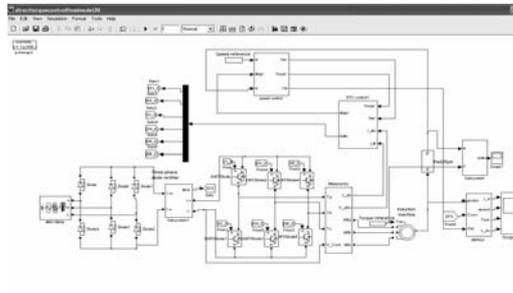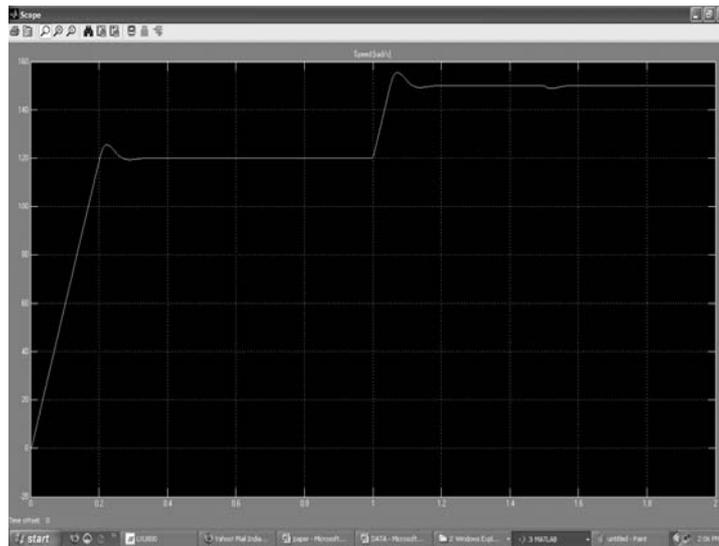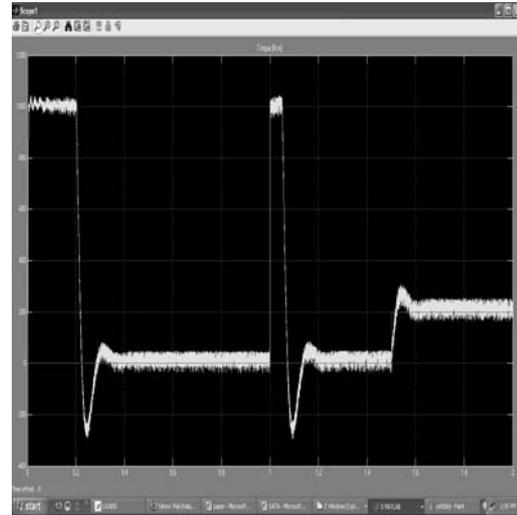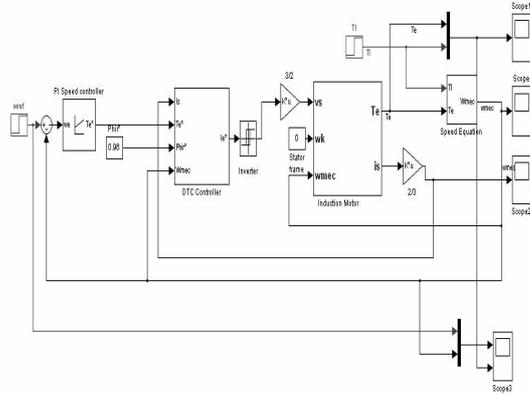
1 TO 8 = MOSFET SWITCHES , 1- TURN ON , 0 – TURN OFF								
VOLTAGE LEVEL	1	2	3	4	5	6	7	8
v/2	0	1	1	0	0	0	1	1
V	1	1	0	0	0	0	1	1
v/2	0	1	1	0	0	0	1	1
-(v/2)	0	0	1	1	0	1	1	0
-v	0	0	1	1	1	1	0	0
- (v/2)	0	0	1	1	0	1	1	0
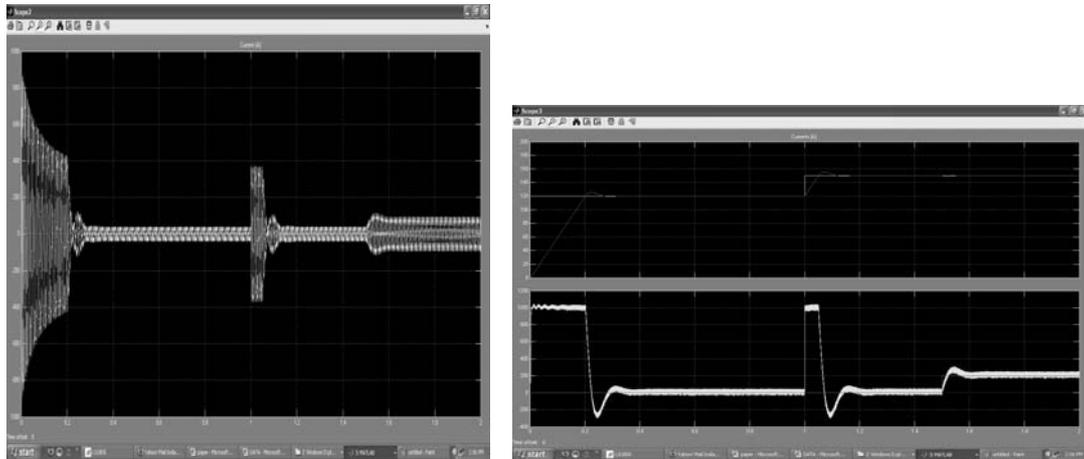
Modeling of Second Level Inverter
Circuit diagram
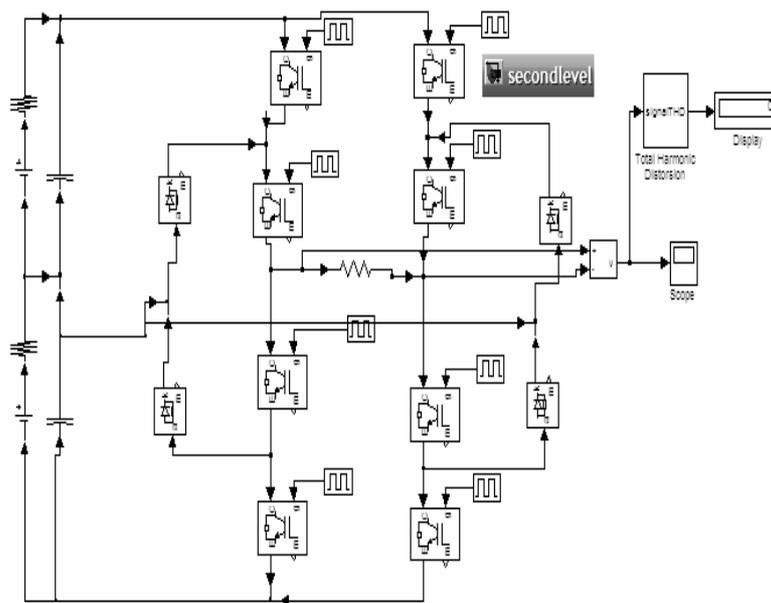
Figure 4.2: Simulation of second level inverter.

Second level

THD VALUE   0.3127
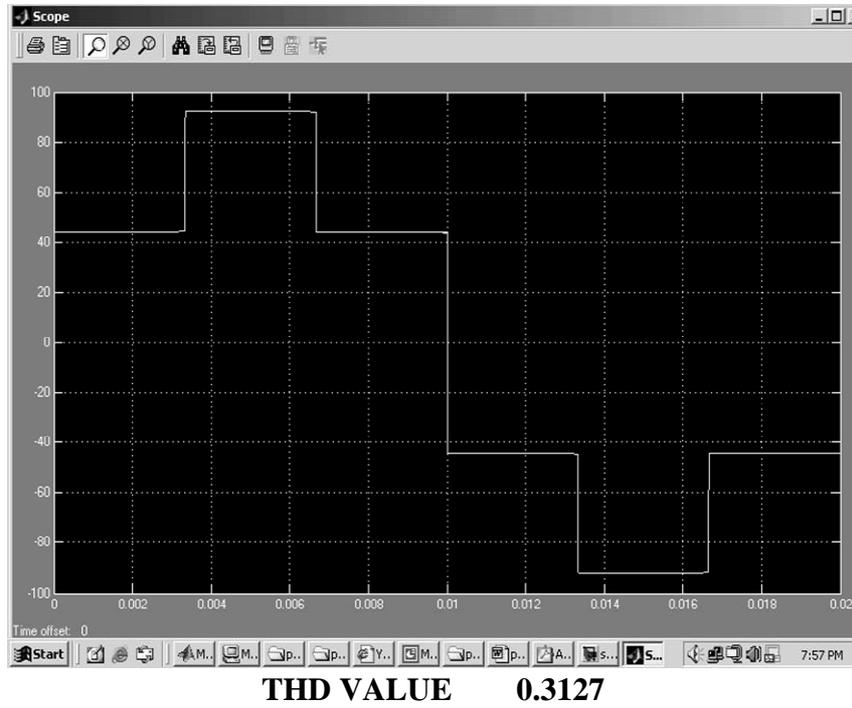
FIG Output of second level inverter

Modeling of Third Level Inverter
Circuit diagram
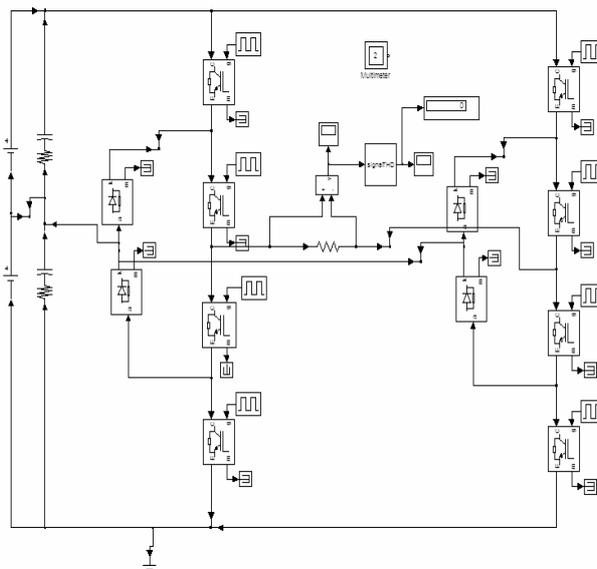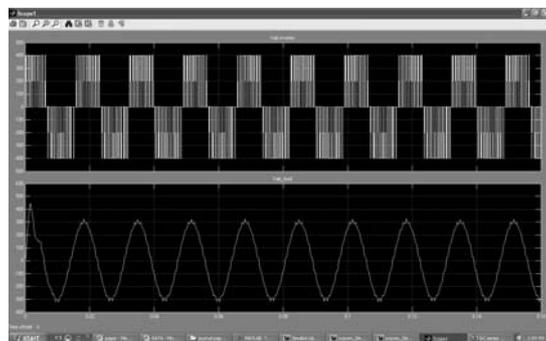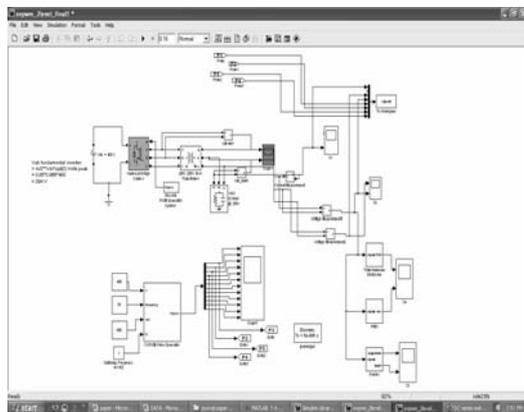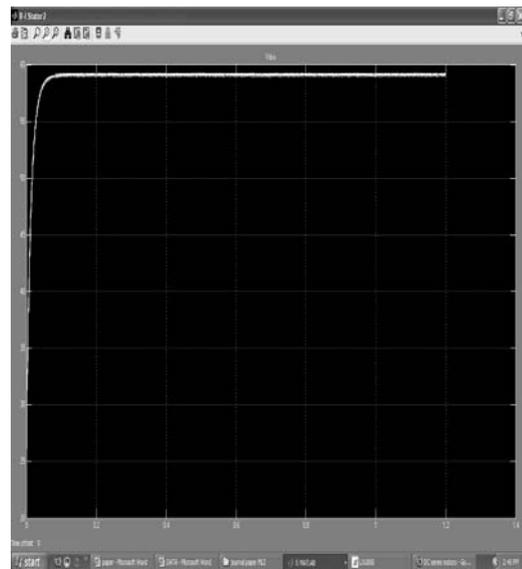

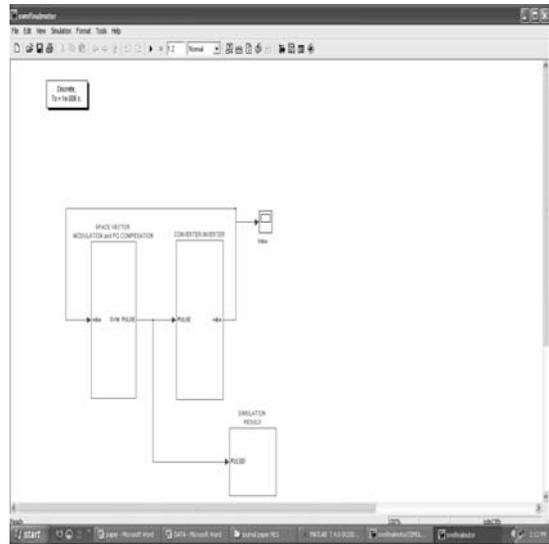**Figure 4.3:** Simulation of third level inverter.

Table No 4: Triggering pulse.

1 TO 8 = MOSFET SWITCHES , 1- TURN ON , 0 – TURN OFF								
VOLTAGE LEVEL	1	2	3	4	5	6	7	8
0	0	0	1	1	0	0	1	1
v/2	0	1	1	0	0	0	1	1
V	1	1	0	0	0	0	1	1
(v/2)	0	1	1	0	0	0	1	1
0	0	0	1	1	0	0	1	1
-(v/2)	0	0	1	1	0	1	1	0
-v	0	0	1	1	1	1	0	0
-(v/2)	0	0	1	1	0	1	1	2
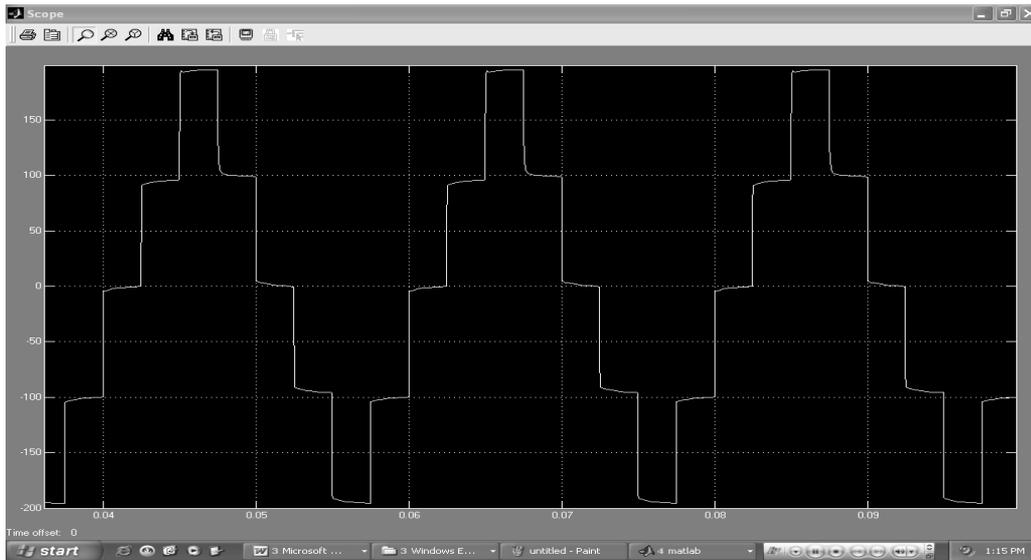
THD = 0.2778

Figure 4.3: Output of third level inverter.
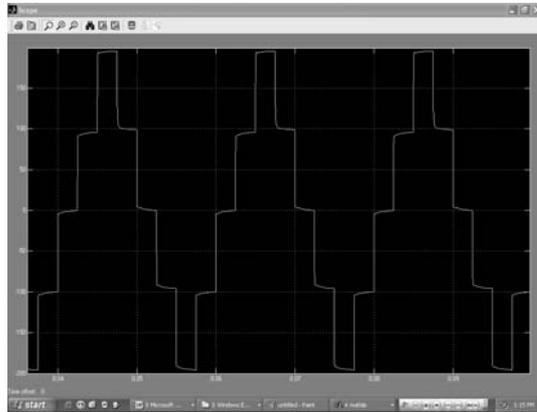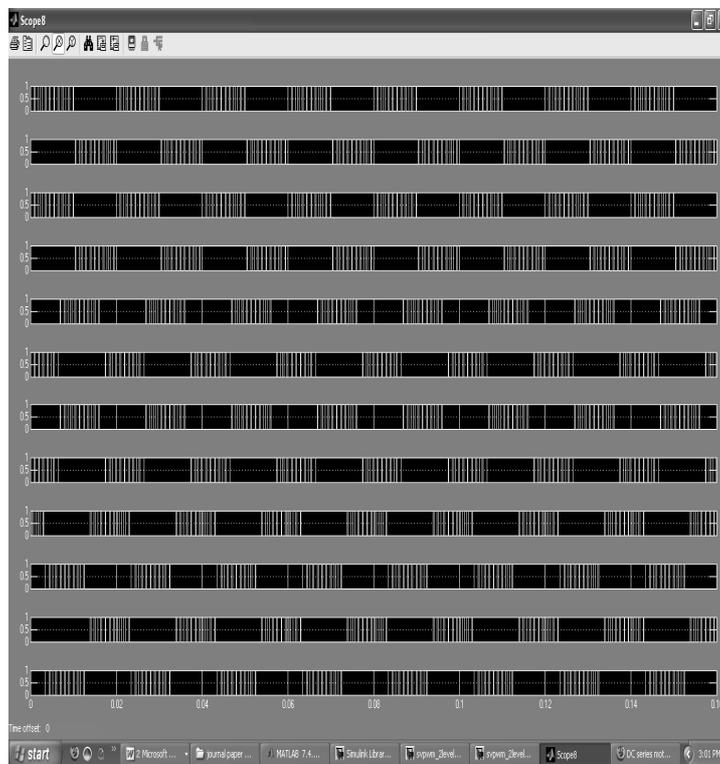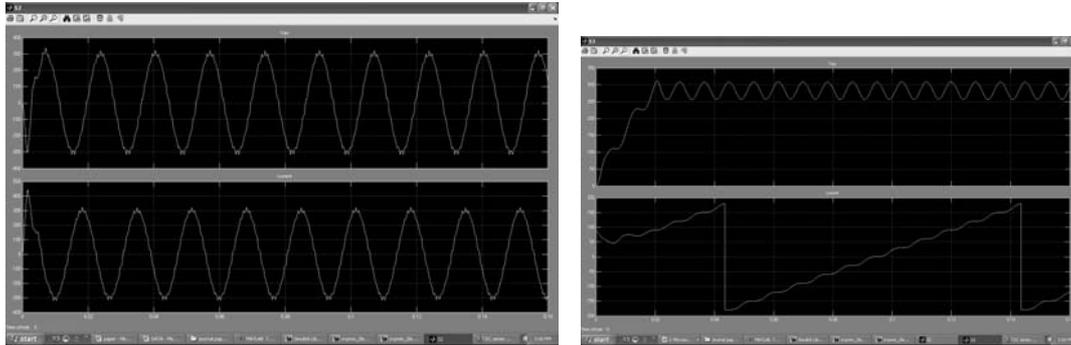
References

[1]   X. Li, R. Duke and S. Round. Development of a threephasethree-level inverter for an electric vehicle. *Australasian Universities Power Engineering Conf.*,Darwin, Australia, 1999, pp 247-251.

[2]   D. W. Novotny and T. A. Lipo. *Vector Control and Dynamics of AC Drive*s, Oxford University Press, 1997.

[3]   J. Holtz. Pulse width Modulation for Electronic Power Conversion. *Proc. of the IEE*E, Vol. 82, No.8, pp. 1194 –1213, Aug 1994.

[4]   I. Takahashi and T. Noguchi. A new quick response and high efficiency control strategy for an induction motor. *IEEE Trans. Industry Applications.* Vol. IA-22, No. 5, pp. 820-827, Sept/Oct 1986.

[5]   T.G. Habetler, F. Profumo, M. Pastorelli, and L.M.Tolbert. Direct Torque Control of Induction Machines using Space Vector Modulation. *IEEETrans. Industry Application*s. Vol. 28, No. 5, Sept/Oct 1992

[6]   J-K. Kang and S-K. Sul. New Direct Torque Control of Induction Motor for Minimum Torque Ripple and Constant Switching Frequency. *IEEETrans. Industry Application*s, Vol. 35, No. 5, Sept/Oct 1999.

[7]   T.A. Lipo and A. Consoli, "Modeling and simulation of induction motors with saturable leakagereactances," IEEE Trans. Ind. Applications, vol. IA-20, pp. 180-198,jan./Feb.1984.

[8]   S.I.Moon and A.Keyhani, "Estimation of inductionmachine parameters from standstill domain data,"IEEE Trans.Ind. Applications, vol.30 pp. 1609-1615.Nov/Dec. 1994.

[9]   Seung-Iii Moon,Ali Keyhani,Srinivas Pillutla,"Nonlinear Neural Network Modeling of an InductionMachine", IEEE Trans. On Control systemstechnology, vol.7,no2, pp. 203-211. March1999.

[10]   "The MATLAB compilers user's guide" in Mathworks hand book Math works 1994.

[11]   Pawel z. Grabowski, Marian.P. Kazmierkowski,B.K.Bose and Frede Blaabjerg'" A simple DirectTorque Neuro-Fuzzy control of PWM inverter FedInduction Motor Drive.

[12]   G.J.Rogers and D.Shirmohammdi, "Inductionmachine modeling for electromagnetic transientprogram," IEEE transactions. Energy conversion, vol,EC-2, pp. 662-668, Dec. 1987.

[13]   A.Keyhani and H.Tsai, "IGSPICE simulation ofinduction machines with saturable inductances," IEEEtransactions. Energy conversion, vol,4, pp. 118-125, Mar.1989.

[14]   Pierre Biden, Thierry Lebey, Member, IEEE, GerardMontrery, Clandice Nealsu and Jacques saint- Michel"Transient voltage distribution in inverter fed motorwindings: Experimental study and Modeling." IEEEtransactions on Power Electronics, vol.16, No.1., Jan.2000.

[15]   Robert T. Novotnak, Member, IEEE, John Chiasson,Member, IEEE, and Marc Bodson, Senior Member,IEEE,"High – Performance Motion control of anInduction motor with Magnetic saturation. IEEEtransactions on Control systems Technology, vol.7, No.3., May. 1999.

[16]   B.J.A. Krose and P.Patrick van der smagt, AnIntroduction to Neural Networks, The University ofAmsterdam, The Netherlands, Sept. 1991.