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# Simplified Space Vector Based Decoupled Switching Strategy for Indirect Vector Controlled Open-End Winding Induction Motor Drive

Syed Munvar Ali, V. Vijaya Kumar Reddy, M. Surya Kalavathi

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***Abstract*****—**In this paper, a dual inverter configuration has been implemented for induction motor drive. This isolated dual inverter is capable to produce high quality of output voltage and minimize common mode voltage (CMV). To this isolated dual inverter a decoupled space vector based pulse width modulation (PWM) technique is proposed. Conventional space vector based PWM (SVPWM) techniques require reference voltage vector calculation and sector identification. The proposed decoupled SVPWM technique generates gating pulses from instantaneous phase voltages and gives a CMV of $\pm v_{dc/6.}$ To evaluate proposed algorithm MATLAB based simulation studies are carried on indirect vector controlled open end winding induction motor drive.

***Keywords*****—**Inverter configuration, decoupled SVPWM, common mode voltage, vector control.

## I. INTRODUCTION

NOWADAYS with the swift developments in semiconductor technology induction motor dives are replacing DC motor drives for industrial applications. Though DC motors give fast response, they have limitation like high weigh to volume ratio and they also require regular maintenance. Induction motor can prevail over these limitations but gives sluggish transient response. To improve the transient response decoupled control is employed to the induction motor drive. This decoupled control can be achieved by direct torque control and field oriented control algorithms. In this work focus is given on field oriented control algorithm.

In vector control algorithm, the independent control of $i_d$ and $i_q$ components of an induction motor are equivalent to a separately excited dc motor [1]. Hence, the name decoupled control is derived. The advancements in the field oriented control algorithm are discussed in [2], [3]. In the field oriented controlled induction motor drive, gate pulses for inverters are derived using stator current hysteresis controllers. With hysteresis controllers control signals are generated with a variable switching frequency. The filter design problems in variable switching frequency operation can be eliminated by the constant switching frequency schemes.

Several constant switching frequency pulse width modulation (PWM) techniques were developed with voltage source inverter in variable v/f control [4]. The switching logic implemented in the PWM reduces the harmonics present in the output voltage and current. Among various PWM algorithms, SVPWM algorithms [5] are gaining importance because of high DC voltage utilization, low harmonic distortion and low switching losses. The conventional SVPWM algorithms are complex to implement because of complexity involved in sector identification and angle calculations. To minimize the complexity, simplified approaches with imaginary switching times are presented [6]-[9].

Though there are many advantages with SVPWM technique it generates high CMV because of zero voltage vectors. High frequency inverters give CMV and leakage currents which may lead to EMI problems with other equipments and bearing failures [10]-[13]. For the reduction of CMV and common mode currents, different active and passive methods were identified [10]-[14]. But, these methods require extra additional hardware and complex to design which may increases the cost. Hence, now for the variable speed drive applications, research has been aimed at the developments of multilevel inverter (MLI) configuration. Different MLI topologies [15]-[19] like cascaded H-bridge, diode clamped and capacitor clamped MLI topologies are gaining importance. These MLI topologies could decrease total harmonic distortion and common mode voltage (CMV) by creating large number of small voltage steps in the pole voltages. But the disadvantages with MLI topologies are the requirement of extra clamping diodes, clamping capacitors and separate DC voltage sources for the operation. Moreover they also suffer from capacitor balancing issues [20], neutral point fluctuations and are complex to operate for higher number of levels. Various modified structures and modified PWM schemes were also proposed to minimize these issues.

In recent years, for high power applications, induction motor drives with open end winding configuration were proposed [21] but they cause load neutral to DC neutral circulating current [22]. The SVPWM inverter gives a two level output with single DC source of $V_{dc}$ voltage with a maximum CMV variation of $\pm V_{dc}/2$ [23]. The proposed decoupled SVPWM dual inverter fed open end winding induction motor drive has isolated inverters with $180^0$ phase

Syed Munvar Ali is with N.B.K.R. Institute of Science and Technology, Andhra Pradesh, PIN 524413, India (corresponding author, phone: +91 988-583-3036; e-mail: syedmunvarali@gmail.com).

V. Vijaya Kumar Reddy is Director of N.B.K.R Institute of Science and Technology, Andhra Pradesh, PIN 524413, India (e-mail: v_vkreddy@yahoo.co.in).

M. Surya Kalavathi is with the Electrical and ElectronicsEngineering Department, J.N.T. University, Hyderabad, Telengana, PIN 500085, India (e-mail: munagala12@yahoo.co.in).

shift between their gate pulses. This drive gives good transient response with reduced CMV of $\pm v_{dc/6}$.

## II. DUAL INVERTER FED OPEN END WINDING INDUCTION MOTOR DRIVE

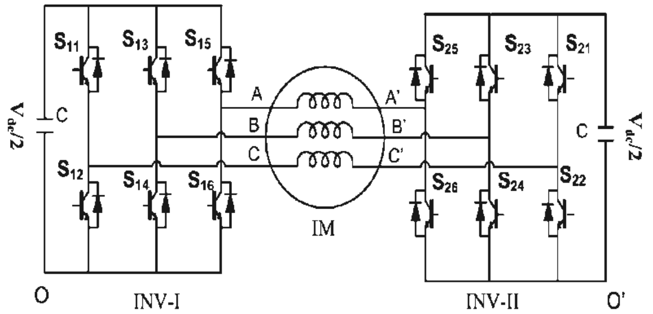


Fig. 1 Dual inverter fed open-end winding induction motor drive

The circuit diagram of isolated dual inverters connecting to open end stator windings of induction motor is shown in Fig. 1. Dual inverters can be connected either to single DC bus (non-isolated DC source) or to an isolated DC bus. Dual inverter with isolated DC bus is able to generate higher number of levels when compared with non-isolated DC bus connection. The dual inverters used in this configuration are capable of generating two-level output voltages independently (i.e. '$\pm V_{dc}/2$' and '0'). Hence the effective output voltage will be generated with three levels (i.e '$+V_{dc}/2$', '0' and '$-V_{dc}/2$') so the configuration is also called as three-level inverter configuration.

Eight switching states are possible for the individual inverters used in the dual inverter configuration. Hence a total 64 switching states are possible for the dual inverter configuration. Among different PWM algorithms, a decoupled control technique is employed in which each inverter is independently controlled to generate effective phase voltage. In the decoupled SVPWM scheme each inverter is operated with reference space vectors as $V_r/2$ and $-V_r/2$ and they will generate an output voltage with phase shift of $180^0$. Since the stator windings in open end winding induction motor are magnetically coupled, the vector addition of $V_r/2$ and $-V_r/2$ results in the generation of actual reference phasor $V_r$, giving a three level inverter structure.

The individual space vectors and their locations on the space vector hexagon of each inverter are shown in Fig. 2. The combined three-level effective space vector hexagon spread over 19 locations is represented in Fig. 3.

The switching sequences used for both inverters in a sampling time period (Ts) are shown in Fig. 4. These switching sequences are obtained assuming the reference space vectors OA and OA' in sectors 1 and 4 respectively. From Fig. 4 it is observed that both the reference vectors have used nearest active and zero vectors to generate the reference phasor. Inverter-I uses 8-1-2-7 and inverter-II uses 8'-5'-4'-7'. Hence the resulting switching sequence is 88'-15'-25'-24'-77' and it gives the three level space vector locations which are possible only when the reference space vectors of inverter-I and inverter-II are phase shifted by $180^0$.

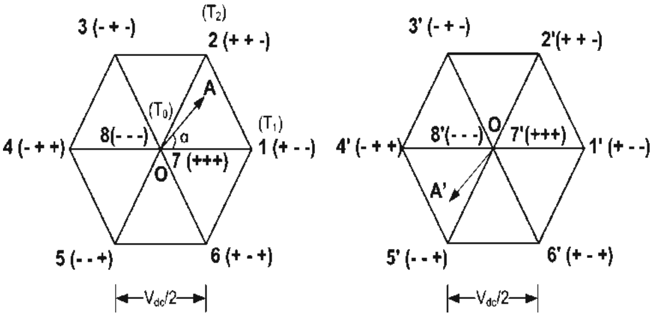


Fig. 2 Space vector locations of the two inverters

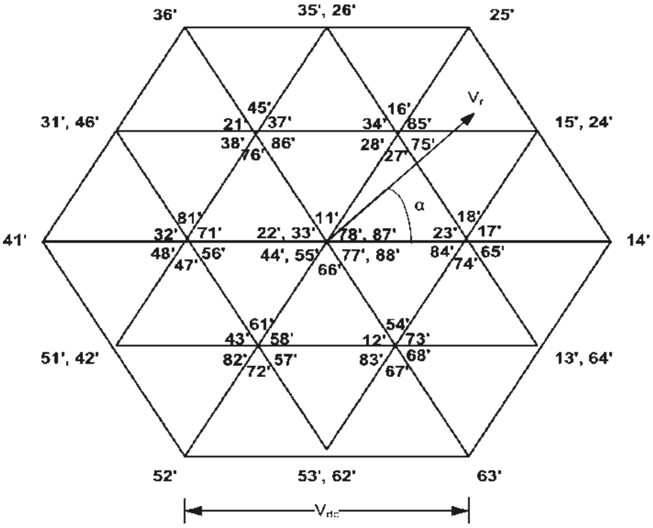


Fig. 3 Space vector locations of open-end winding three-level inverter

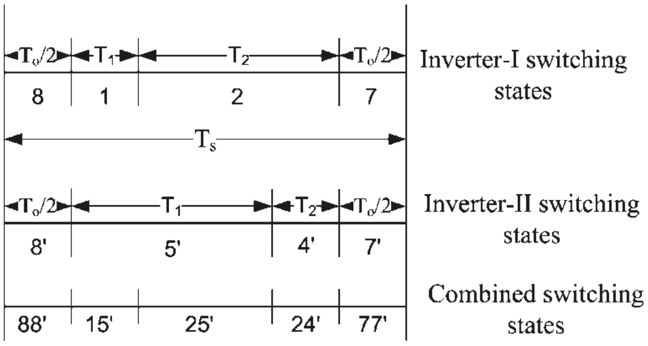


Fig. 4 Timing distribution of the gating pulses for two inverters in one sampling interval

## III. SIMPLIFIED DECOUPLED SVPWM

The PWM techniques can be implemented based on generating modulating signal and digital (1 or 0) space vector approach. In carrier comparison method, modulating signal is generated based on space vector approach. However in any approach to generate gating signals three reference signals have to be considered as given in (1)

$$\begin{aligned} V_{as} &= \cos(wt) \\ V_{bs} &= \cos(wt - 120) \\ V_{cs} &= \cos(wt - 240) \end{aligned} \tag{1}$$

To generate the reference vector, the gating signals for inverter-II are to be shifted by $180^0$. So, one more new set of reference signals for inverter-II are considered as in (2)

$$\begin{aligned} V_{as} &= \cos(wt - 180) \\ V_{bs} &= \cos(wt - 120 - 180) \\ V_{cs} &= \cos(wt - 240 - 180) \end{aligned} \tag{2}$$

From these two sets of reference signals, the gating signal's dwell switching times for both the inverters are calculated by (3)

$$\begin{aligned} T_1 &= \frac{T_s}{V_{dc}}(V_{\max} - V_{mid}) \\ T_2 &= \frac{T_s}{V_{dc}}(V_{mid} - V_{\min}) \\ Tz &= T_s - T_1 - T_2 \end{aligned} \tag{3}$$

where $V_{max}$ and $V_{min}$ are the high and low values of reference signals, Vdc is the normalised DC bus voltage. Using (3) the dwell switching times for each inverter are derived independently. Here active vectors and zero vector times are assigned with T1, T2 and Tz respectively. In the present considered sequence, two zero vectors are used and the zero vector time Tz is divided into two equal halves between those zero vectors.

TABLE I
SWITCHING SEQUENCES OF INVERTER-I AND INVERTER-II

| Sector | Switching Vectors of Inverter-I | Switching vectors of Inverter-II |
|---|---|---|
| 1 | 8127-7218 | 8'5'4'7'-7'4'5'8' |
| 2 | 8327-7238 | 8'5'6'7'-7'6'5'8' |
| 3 | 8347-7438 | 8'1'6'7'-7'6'1'8' |
| 4 | 8547-7458 | 8'1'2'7'-7'2'1'8' |
| 5 | 8567-7658 | 8'3'2'7'-7'2'3'8' |
| 6 | 8167-7618 | 8'3'4'7'-7'4'3'8' |

$V_8$ and $V_7$ are zero voltage vectors and $V_1$ through $V_6$ are active voltage vectors. Using the switching vectors as given in Table I and dwell switching times, gating signals are derived for inverter-I and inverter-II.

## IV. INDIRECT VECTOR CONTROLLED OPERATION OF THE DRIVE

To achieve decoupled control, the stator current vector is to be resolved into d-axis and q-axis components. d-axis current component is the torque controlling component and q-axis current component is the flux controlling component. Hence by controlling $I_{ds}$ and $I_{qs}$, torque and flux are independently controlled in indirect vector controlled open end winding induction motor drive shown in Fig. 5. In the block diagram, the reference d-axis and q-axis current components are calculated and they are compared with actual d-axis and q-axis components. Before comparing the actual current components with reference current components, the actual current components are transformed into synchronous reference frame where d-axis and q-axis actual current components appear as DC quantities. The obtained current error components are fed to the PI controllers which generate two phase reference voltage signals. These two axis reference voltage signals are transformed into three phase reference signals and fed to decoupled PWM algorithm block. In this block the obtained reference signals can be considered equivalent to that as of (1). Using these reference signals the required gating signals to both the inverters are generated as discussed in Section III.

## V. SIMULATION RESULTS AND DISCUSSIONS

The performance of the indirect vector controlled open end winding induction motor drive is evaluated in the MATLAB/ Simulink environment and motor specification parameters are $R_s$=1.57Ω, $R_r$ =1.21Ω, $L_s$=0.17H,$L_r$=0.17H, $L_m$ =0.165 H, J = 0.089 Kg.$m^2$.

The constant switching frequency of each inverter is taken as 3 kHz. The DC input voltage of 540 V is shared as 270 V to each inverter. The reference speed was set at 1000 rpm. The results of indirect vector controlled open end winding induction motor drive are presented for transient, steady state and loading conditions. Fig. 6 shows transient behavior during starting, Fig. 7 shows steady state response and Fig. 8 shows transient during load condition. In all conditions, the results were taken for pole voltage, effective phase voltage, CMV, speed, torque and three phase line currents. This isolated dual two level inverter generates three level output phase voltages. The voltage levels have the magnitudes of $V_{dc}/3$, $V_{dc}/2$ and $2V_{dc}/3$. The magnitude of common mode is equal to $\pm V_{dc}/6$. From the results it is observed that the CMV magnitude is reduced when compared with two level inverter fed induction motor drive. From Fig. 8 it is observed that a load of 25 Nm is applied and only a small reduction is observed. Hence the controllers are robust.

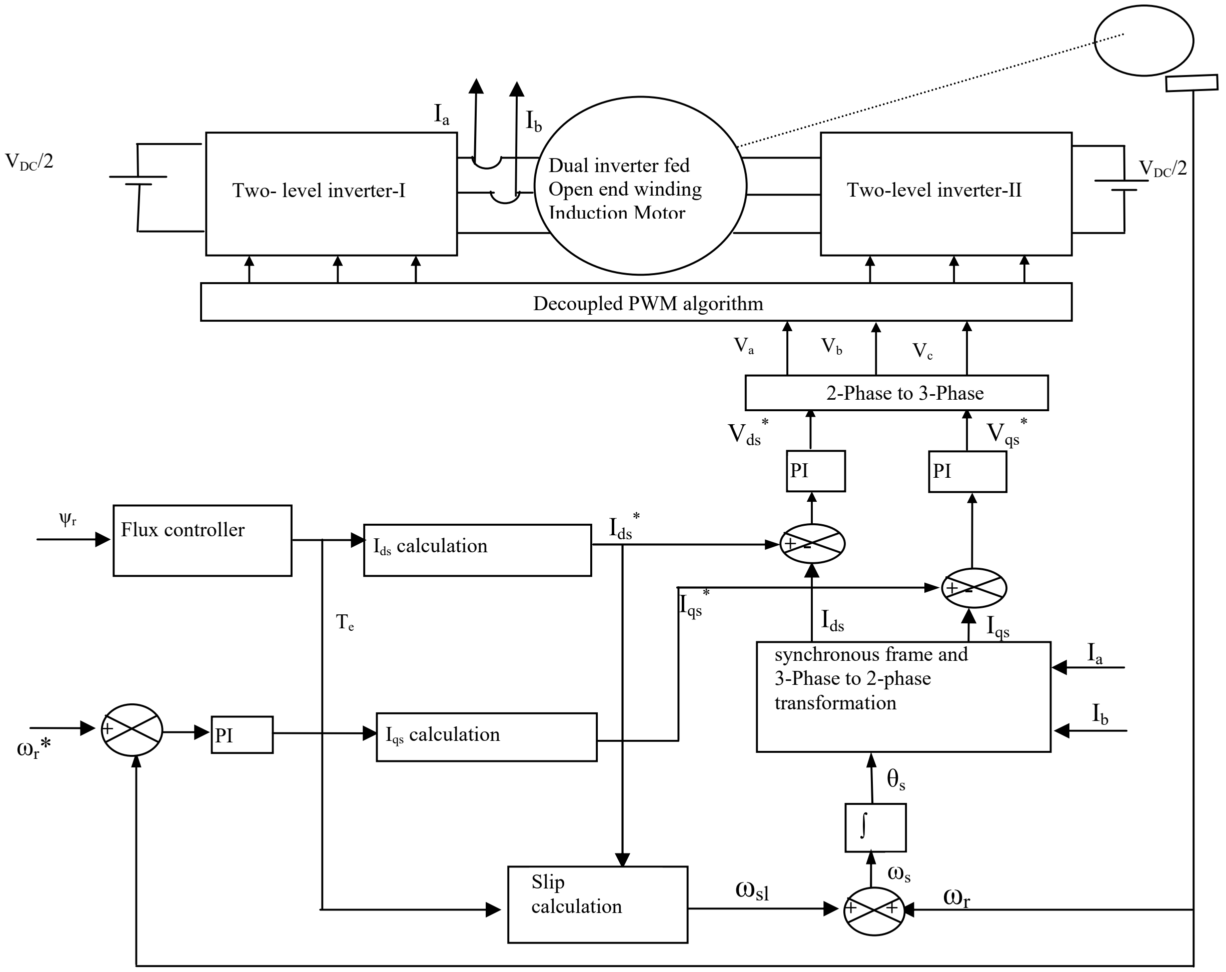
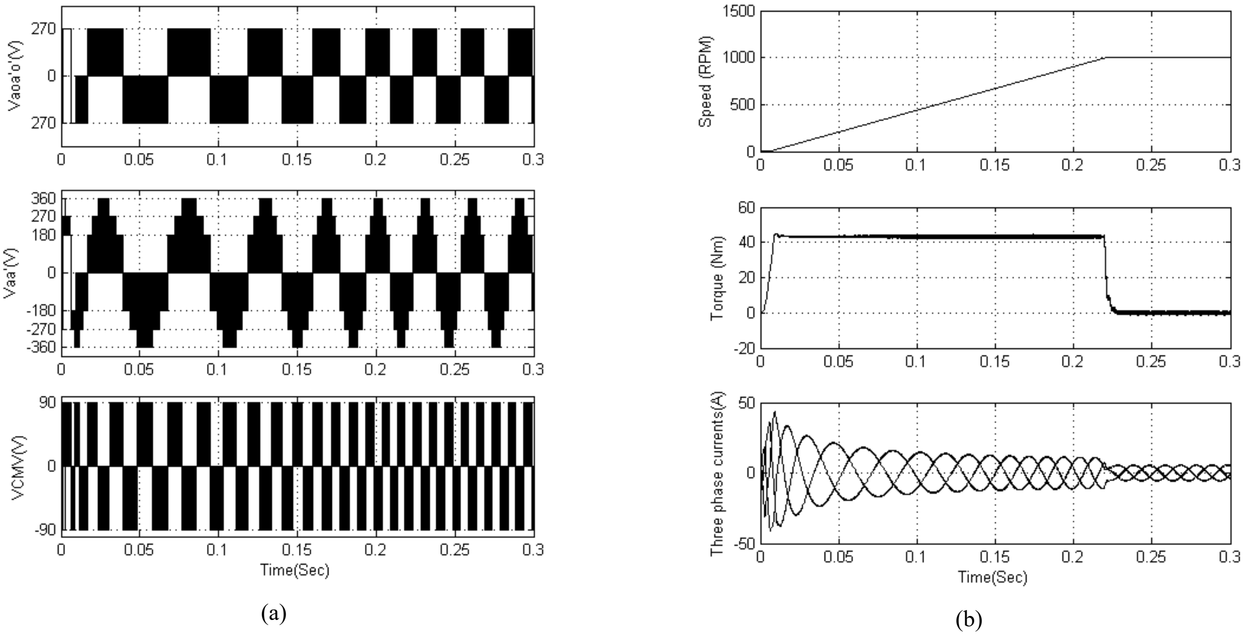


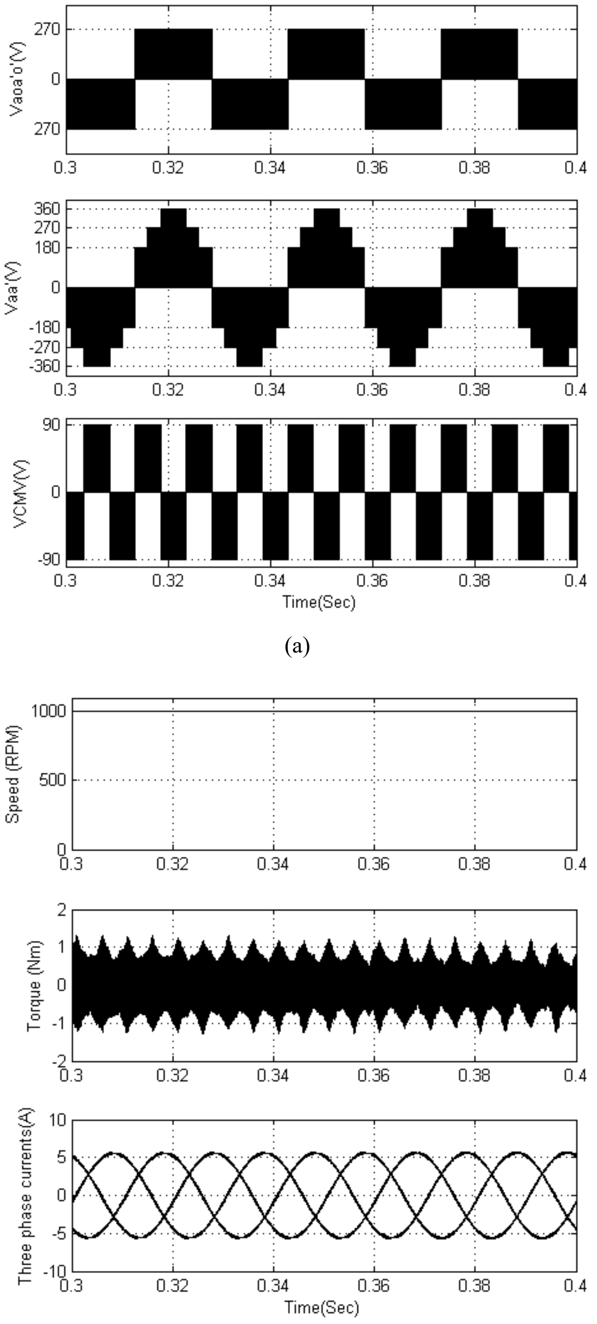
Fig. 5 Block diagram of indirect vector controlled open end winding induction motor drive



(a)

(b)

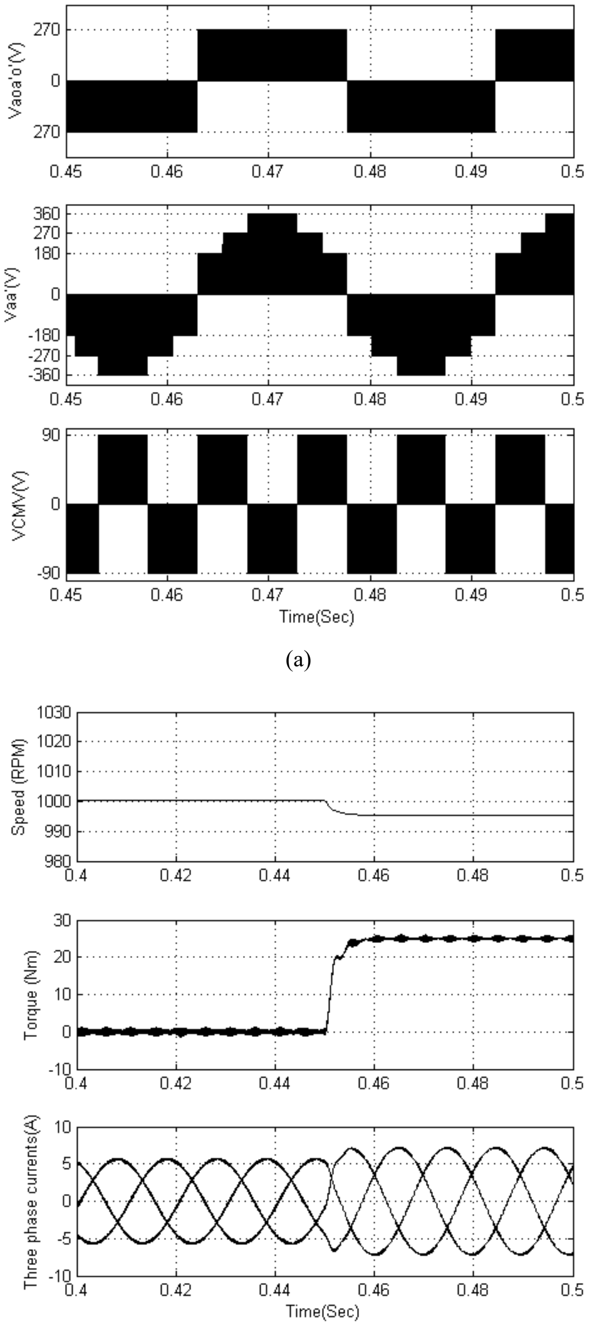
Fig. 6 Starting transients of indirect vector controlled open end winding induction motor drive



(a)

(b)

Fig. 7 Steady state results of indirect vector controlled open end winding induction motor drive



(a)

(b)

Fig. 8 Transients during load condition of indirect vector controlled open end winding induction motor drive

## VI. CONCLUSIONS

From the numerical studies of indirect vector controlled open end winding induction motor drive, it is concluded that the drive has fast transient response because of decoupled control. This drive produces higher number of voltage levels when compared with two-level inverter fed induction motor drive. Hence the CMV and problems related to CMV are reduced.

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