

# DECOUPLED SVPWM ALGORITHM FOR OPEN-END WINDING INDUCTION MOTOR DRIVE

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**Abstract:** — In now a days modern multi level inverters have emerged to overcome the drawbacks due to the conventional inverters. In various industries inverters with different PWM techniques have been employed to achieve good performance in the context of variable speed drives. But due to multilevel inverters the switching losses are more and the cost of the equipment is also more because of the number of devices is increased in multilevel inverters. These are some drawbacks due to the usage of conventional multilevel inverters in industries. In this proposed work a decoupled algorithm is proposed to overcome the drawbacks due to conventional inverter have been presented. The cascaded connection of asynchronous motor and two 2-level inverters at both ends of motor constitutes to open end winding induction motor drive. The characteristics of dual inverter fed open end winding induction motor drive resembles to those of conventional three level inverter. In this proposed work the performance characteristics of Induction motor with different PWM techniques like CSVPWM, DPWMMAX, DPWMMIN have been analysed using MATLAB/SIMULINK environment and to validate the results the harmonic spectra values has been listed out.

**Key words:** Bearing currents, CSVPWM, Decoupled algorithm, Open end winding induction motor drive, Modulation index.

## 1.Introduction

Conventional two level inverters are extensively used in medium voltage and high power variable speed drive systems because of their inherent switching operation but however have some limitations in operating at high frequency mainly due to switching losses and constraints of device rating. These switching converters can also provokes high dv/dt caused due to the switching transients[1-2]. These zero sequence voltages results into various adverse effects on motors named as bearing currents, conducted electromagnetic interference, ground currents through stray capacitors. In consequence to this premature motor bearing failures will occur. The clear indication of flowing of hazardous bearing currents in the context of motors inside the motors can be shown in the Fig.1.

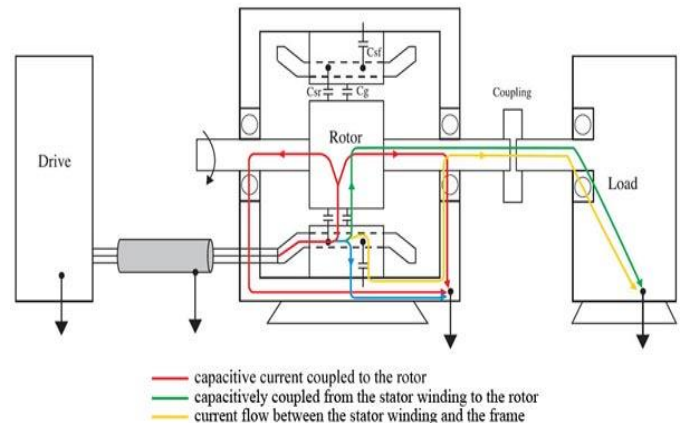


Fig.1 Flow of bearing currents inside the motor

So concerning to this the hazardous common mode voltages in the context of variable speed motors has to be mitigated [4,10].

The numerous methods for mitigating common mode voltage in inverters can be classified as[4]:

[A].Using isolation transformers, Common mode choke, Using hybrid active and passive filters, Using dual inverter fed open end winding induction motor drive, Using four phase inverter.

[B].Using some advanced modulation techniques like carrier based SVPWM scheme for dual inverter fed open end winding IM drive.

The methods proposed in [A] above increases the system cost as it employs some extra hardware circuitary and complexity in control. So this is mainly focused on the implementation of SVPWM technique for dual inverter fed open end winding induction motor. A schematic of dual inverter fed open end winding induction motor can be represented as shown in the Fig.2.

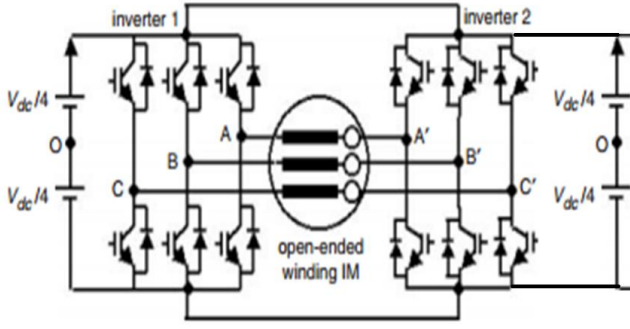


Fig.2 Dual inverter fed open end winding Induction motor drive

As dual inverter fed open end winding induction motor drive resembles the performance of three level inverter thus we can achieve multilevel inverter operation using this configuration. Hence the harmonic content of the output voltage waveform decreases significantly, dv/dt stresses are reduced, Produces smaller zero sequence voltages therefore stress in the bearings of motor can be reduced, Provides low switching losses and higher efficiency[5-8].

## 2.Multi level inverter operation with open end winding induction motor:

A remedy for the production of flowing of bearing currents inside the motors is open end winding induction motor. In this configuration Induction motor is fed by two inverters from either side which are operated by isolated power supplies. A schematic diagram of dual inverter fed induction motor is represented as shown in Fig.3.

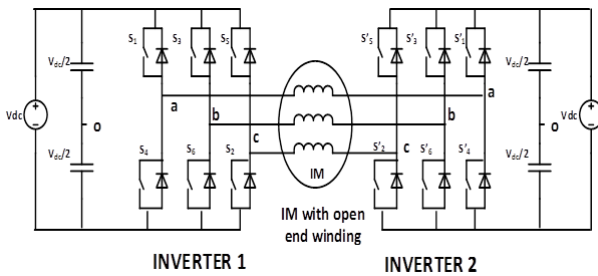


Fig.3 Dual inverter fed open end winding IM drive

Here  $S_1, S_2, S_3, S_4, S_5, S_6$  are the switches of inverter 1 and  $S_1', S_2', S_3', S_4', S_5', S_6'$  are the switches of inverter 2. The two inverters are supplied with isolated DC links, If the isolated DC link voltages are equal (i.e.  $V_{S1}=V_{DC}/2$  &  $V_{S2}=V_{DC}/2$ ) then the configuration resembles to that of three level inverter drive. If the Isolated DC link voltages are unequal (i.e.  $V_{S1}=2V_{DC}/3$  &  $V_{S2}=V_{DC}/3$ ) then the configuration resembles to that of four level inverter. In this 1 & 0 represents on states of switches of inverter 1, 1' & 0'

represents on states of switches of inverter2. For the three level inverter the levels of voltage in the output voltage are  $+V_{dc}/2, 0, -V_{dc}/2$ . For the four level inverter the levels of voltages in the output voltage are  $+V_{dc}/2, +V_{dc}/6, -V_{dc}/6, -V_{dc}/2$ .

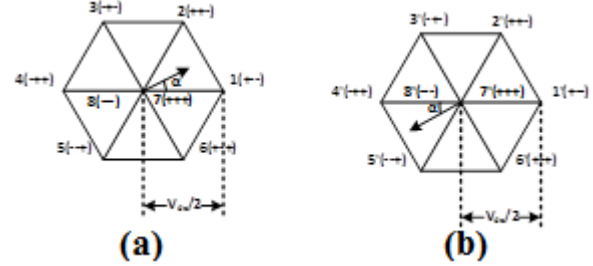


Fig.4 Space vectors of two individual inverters  
(a) Inverter-1 (b) Inverter-2

Here first space vector corresponds to Inverter-1 & the reference vector is switched in sector-1 between first two active vectors  $V_1$  &  $V_2$ , at an angle  $\alpha$  w.r.t first active vector  $V_1$ . And the second space vector corresponds to Inverter-2 & the reference vector is switched in sector-4 between  $V_4$  &  $V_5$  at an angle  $\alpha$  i.e.  $180^\circ + \alpha$  w.r.t  $V_1$ , the reference vector of first space vector & reference vector of second space vector are  $180^\circ$  apart. But the supply voltages for the two inverters are same i.e.  $V_{dc}/2$  for dual inverter(three level operation).

Here  $V_{A0}, V_{B0}, V_{C0}$  are the pole voltages of inverter 1,  $V_{A0}', V_{B0}', V_{C0}'$  are the pole voltages of inverter 2.  $V_{AA}, V_{BB}, V_{CC}$  are the Phase voltages of the inverter which are supplied to the three phase induction motor but here the sum of all these phase voltages is not equal to zero, which results as zero sequence component in motor due this the bearing currents will flow inside the motor. But here carrier based SVPWM algorithm is proposed to mitigate this Common mode voltage. The three phase voltages of dual inverter fed induction motor drive is given by

$$\left. \begin{aligned} V_{AA}' &= V_{A0} - V_{A0}' \\ V_{BB}' &= V_{B0} - V_{B0}' \\ V_{CC}' &= V_{C0} - V_{C0}' \end{aligned} \right\} \quad (7)$$

Where  $V_{A0}, V_{B0}, V_{C0}$  are the pole voltages of inverter 1,  
 $V_{A0}', V_{B0}', V_{C0}'$  are the pole voltages of inverter 2  
 &  $V_{AA}, V_{BB}, V_{CC}$  are the Phase voltages of the inverter

The common mode voltage or Zero sequence voltage is given by

$$CMV \text{ or } V_{zs} = \frac{V_{AA}' + V_{BB}' + V_{CC}'}{3} \quad (8)$$

The reference voltage in SVPWM modulation technique will be obtained as represented in equation (4)

$$V_{ref} = V_{AA}' + V_{BB}' e^{j2\pi/3} + V_{CC}' e^{j4\pi/3} \quad (9)$$

Hence by employing this open end winding configuration multilevel inverter operation can be achieved and the problems due to conventional inverters like common mode voltages can be overcome.

### 3. Decoupled PWM technique

The procedure described in [6] uses the instantaneous reference voltages and is based on the concept of 'effective time'. The effective time is expressed as the time "For which the motor is supplied by the inverter voltage and is designated as  $T_{eff}$ . The sampling time period is designated as  $T_s$ . The instantaneous phase reference voltages are acquired by projecting the tip of the reference vector  $V_{sr}$  on to the corresponding phase axes & these projections have to be multiplied with a factor of  $(2/3)$ . The factor  $(2/3)$  is multiplied to the projections because of the 'Two to Three phase' transformation. These instantaneous phase reference voltages are indicated as  $V_a^*$ ,  $V_b^*$  and  $V_c^*$ . The symbols  $T_{ga}$ ,  $T_{gb}$  and  $T_{gc}$  respectively signifies the time spell for which a given motor phase is connected to the positive rail of the input DC power supply of the inverter in the given sampling time period  $T_s$ . The timings  $T_{ga}$ ,  $T_{gb}$  and  $T_{gc}$  are labelled as the phase switching times. The procedure to generate the gating pulses for the individual devices using this algorithm is elaborately explained in [10].

For a dual inverter system, there would be two sets of phase switching times, one for each inverter. The phase switching timings of inverter-1 are represented by the symbols  $T_{ga}$ ,  $T_{gb}$  and  $T_{gc}$ . while the symbols  $T'_{ga}$ ,  $T'_{gb}$  and  $T'_{gc}$  denote the same for inverter-2.

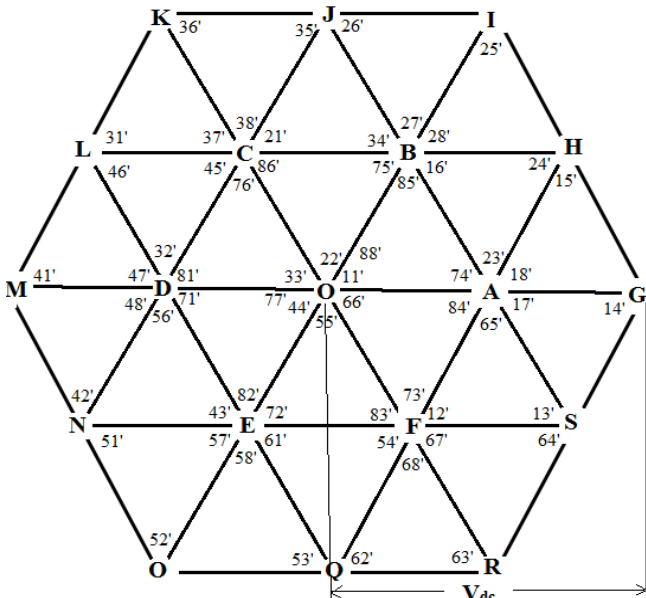


Fig.5. Resultant space vector combinations in the dual inverter scheme

There are two distinct PWM strategies:

- (1) Decoupled PWM strategy
- (2) The alternative inverter switching strategy.

For achieving three level inverter operation with dual inverter configuration the space vector corresponds to the inverter-2 is overlaid on the space vector of inverter1. After superimposing space vector of inverter-2 on space vector of inverter-1 there exists a centre hexagon (ABCDEF) with a centre named as O, covered by six sub hexagons signified as OBHGSF, OCJIHA, ODLKJB, OENMLC, OFQPND and OASRQE having centres at A,B,C,D,E,F respectively as shown in the Fig.5.

This Decoupled PWM strategy mainly focusses on the concept that the reference voltage space vector  $V_{sr}$  can be formulated with two opposite components  $V_{sr}/2$  and  $-V_{sr}/2$ . Subtraction of the second component from the first component achieves the anticipated reconstruction of the reference vector. In other words, it is based on the observation that the effect of applying a vector with inverter-1 while inverter-2 assumes a null state is twice as that of applying the opposite vector with inverter-2 while inverter-1 assumes a null state. The decoupled PWM strategy is as shown in the Fig.5 & Fig.6.

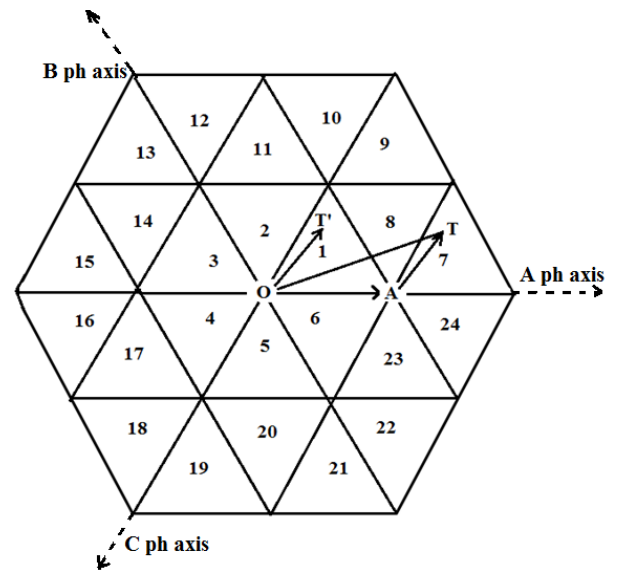


Fig.6. Reference vector for three level voltages

It is worth noting that the phase axes of the motor viewed with reference to individual inverters are in phase opposition. In Fig.5 and Fig. 6, the vector  $OT$  signifies the actual reference voltage space vector, & it has to be synthesized from the dual-inverter system and is specified by  $|V_{sr}| \angle \alpha$ . This vector is resolved into two opposite components  $OT1$  is  $(|V_{sr}|/2 \angle \alpha)$  and  $OT2$  is  $(|V_{sr}|/2 \angle 180^\circ + \alpha)$ . The vector  $OT1$  is synthesized by inverter-1 by switching among the states (8 1 2 7) while the vector  $OT2$  is reconstructed by inverter-2 by switching among the states (8' 5' 4' 7'). The advantage with the recommended decoupled control is that the inverter switching timings of both the inverters need not be computed. However, in this strategy, both the inverters have to be switched.

#### 4.SIMULATION RESULTS

##### A)For single inverter Fed IM drive with SVPWM control:

A two level inverter fed induction motor drive is modelled and is simulated by employing space vector pulse width modulation(SVPWM) control technique with Modulation index=0.8(Under modulation) and the Modulated waveform, output pole voltage, Line voltage, phase voltages and the common mode voltage of the inverter are shown in Fig.7.

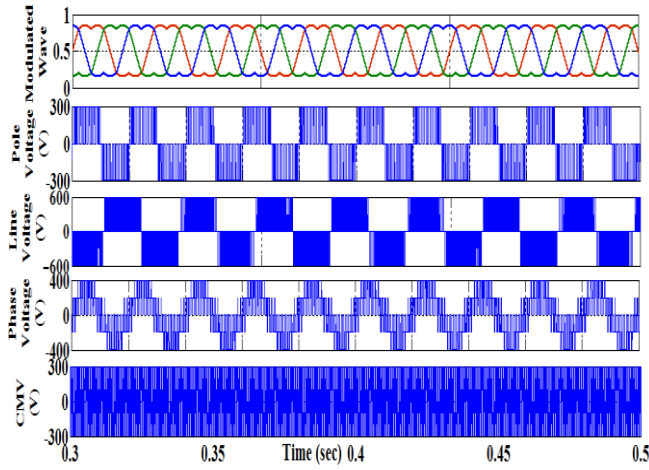


Fig.7 Modulated wave, Pole voltage, Line Voltage, Phase Voltage, CMV for Single inverter with SVPWM

The performance characteristics of Induction motor drive i.e. Stator currents, Torque response, Speed response at no load are as shown in Fig.7. The motor achieves steady state at 0.3 sec. The Total Harmonic Distortion(THD) for the stator currents is 7.26% for this model.

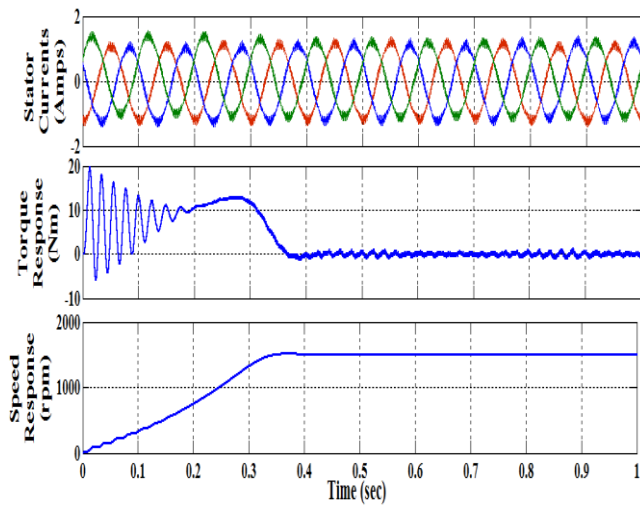


Fig.8 Performance characteristics of IM drive with single inverter(SVPWM) at steady state

##### B)For dual inverter Fed IM drive(three level inverter operation) with CSVPWM, DPWMMAX,DPWMMIN control

A dual inverter fed induction motor drive is modelled and is simulated by employing space vector pulse width modulation(CSVPWM) control technique and the Modulated waveform, output pole voltage, Line voltage, phase voltage and the common mode voltage of the inverter which resembles the characteristics of three level inverter characteristics are shown in Fig.9.

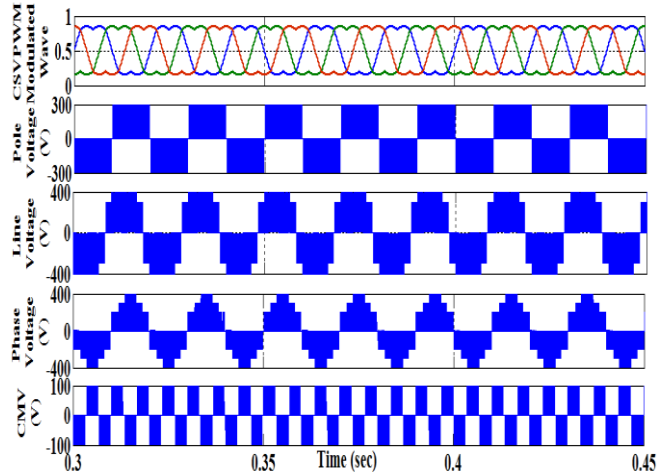


Fig.9 Modulating Wave, Pole voltage, Line Voltage, Phase Voltage, Common mode voltage for dual inverter (Three level inverter operation)with CSVPWM control technique

The performance characteristics of Induction motor drive i.e. Stator currents, Torque response, Speed response at no load are as shown in Fig.10. The motor achieves steady state at 0.25 sec. The Total Harmonic Distortion(THD) for the stator currents is 4.77% for this model & the common mode voltage is mitigated compared to single inverter fed IM drive.

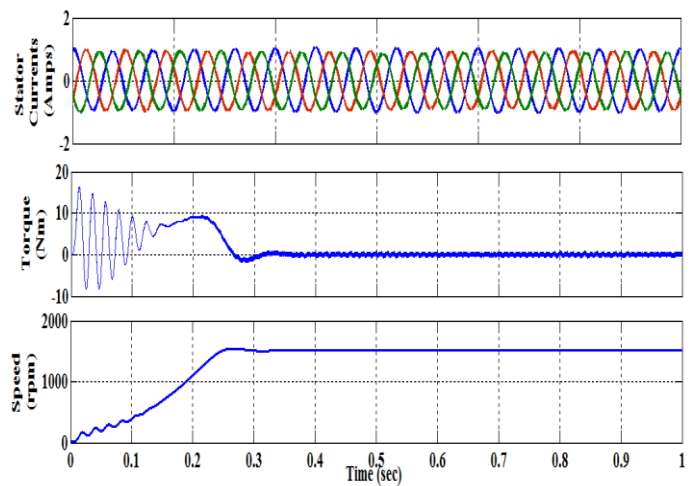


Fig.10 Performance characteristics of dual inverter (Three level inverter operation(CSVPWM))fed IM drive at steady state



A dual inverter fed induction motor drive is modelled and is simulated by employing space vector pulse width modulation(DPWMMAX)control technique and the Modulated waveform, output pole voltage, Line voltage, phase voltages and the common mode voltage of the inverter which resembles the characteristics of three level inverter characteristics are shown in Fig.11.

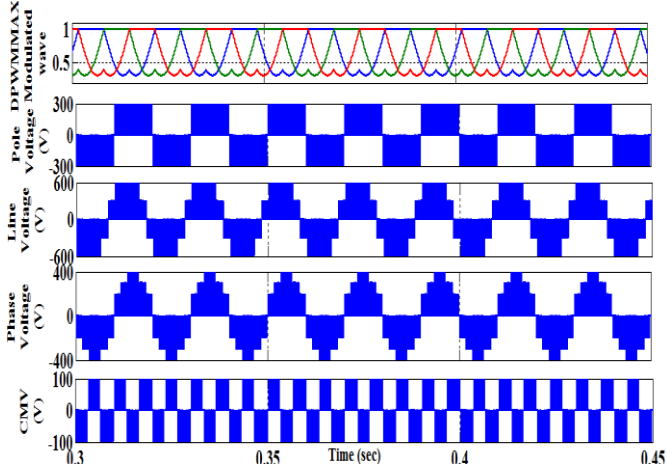


Fig.11 Modulating Wave, Pole voltage, Line voltage, Phase Voltage, common mode voltage for dual inverter (Three level inverter operation)with DPWMMAX control technique

The performance characteristics of of dual inverter fed Induction motor drive(three level inverter operation)with DPWMMAX control i.e. Stator currents, Torque response, Speed response at no load is as shown in Fig.12. The motor achieves steady state at 0.25 sec and the Total Harmonic Distorsion(THD) for the stator currents is 3.97% for this model & the common mode voltage is mitigated compared to single inverter fed IM drive.

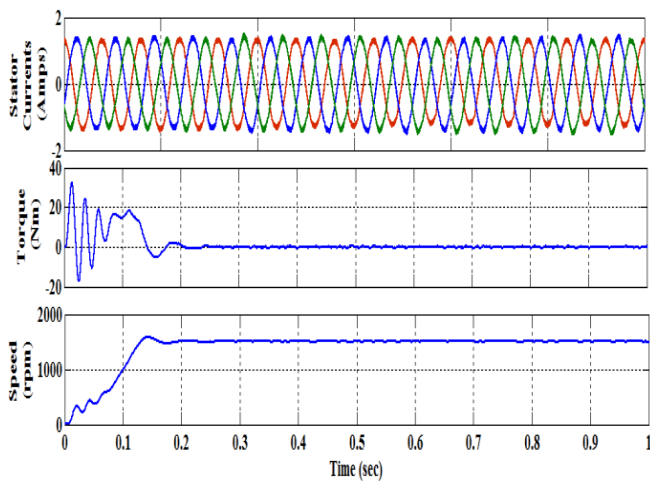


Fig.12 Performance characteristics of dual inverter (Three level inverter operation with DPWMMAX)fed IM drive at steady state

A dual inverter fed induction motor drive is modelled and is simulated by employing space vector pulse width modulation(DPWMMIN)control technique and the Modulated waveform, output pole, Line voltage, phase voltages and the common mode voltage of the inverter which resembles the characteristics of three level inverter characteristics are shown in Fig.13.

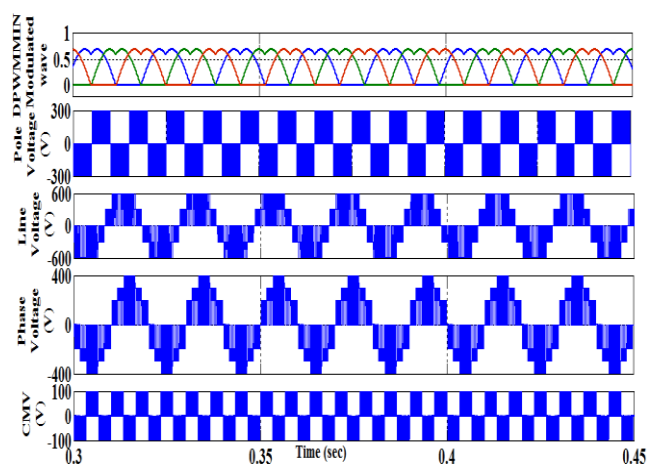


Fig.13 Modulating Wave, Pole voltage, Phase Voltage, common mode voltage for dual inverter (Three level inverter operation)with DPWMMIN control technique

The performance characteristics of of dual inverter fed Induction motor drive(three level inverter operation)with DPWMMIN control i.e. Stator currents, Torque response, Speed response at no load are as shown in Fig.14. The motor achieves steady state at 0.25 sec.The Total Harmonic Distortion (THD) for the stator currents is 3.85% for this model & the common mode voltage is mitigated compared to single inverter fed IM drive.

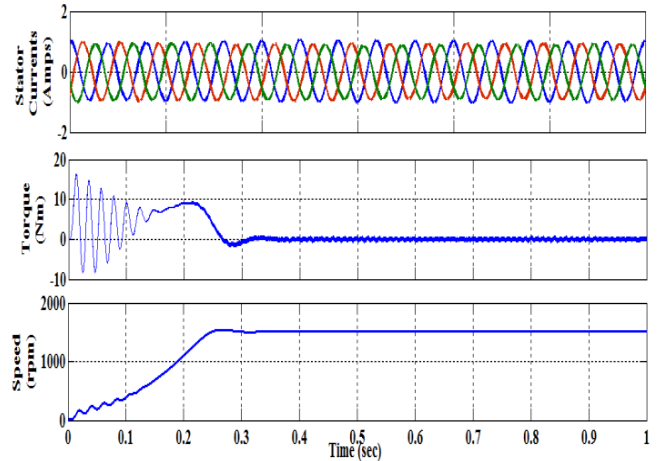


Fig.14 Performance characteristics of dual inverter (Three level inverter operation with DPWMMIN control) fed IM drive at steady state

**C)For dual inverter Fed IM drive(Four level inverter operation)with CSVPWM, DPWMMAX,DPWMMIN control**

A dual inverter fed induction motor drive is modelled and is simulated by employing space vector pulse width modulation(CSVPWM) control technique and the Modulated waveform, output pole voltage, Line voltage, phase voltage and the common mode voltage of the inverter which resembles the characteristics of four level inverter characteristics are as shown in Fig.15.

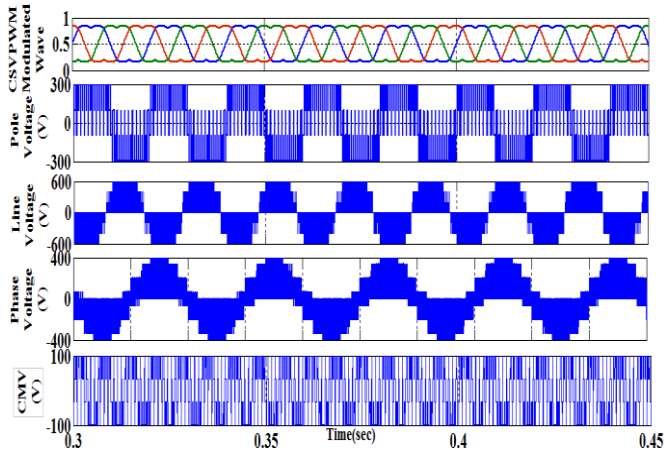


Fig.15 Modulated wave, Pole voltage, Line voltage, Phase voltage, Common mode voltage for dual inverter(Four level inverter operation with CSVPWM control)

The performance characteristics of of dual inverter fed Induction motor drive(four level inverter operation)with CSVPWM control i.e. Stator currents, Torque response, Speed response at no load are as shown in Fig.16. The motor achieves steady state at 0.25 sec.The Total Harmonic Distorsion (THD) for the stator currents is 4.77% for this model & the common mode voltage is mitigated compared to dual inverter fed IM drive with three level inverter operation.

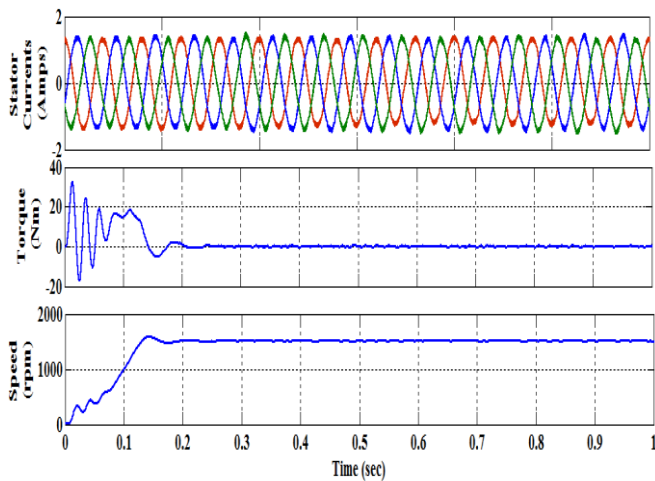


Fig.16 Performance characteristics of dual inverter (Four level inverter operation(CSVPWM))Fed IM drive at steady state

A dual inverter fed induction motor drive is modelled and is simulated by employing space vector pulse width modulation(DPWMAX) control technique and the Modulated waveform, output pole voltage, Line voltage, phase voltage and the common mode voltage of the inverter which resembles the characteristics of four level inverter

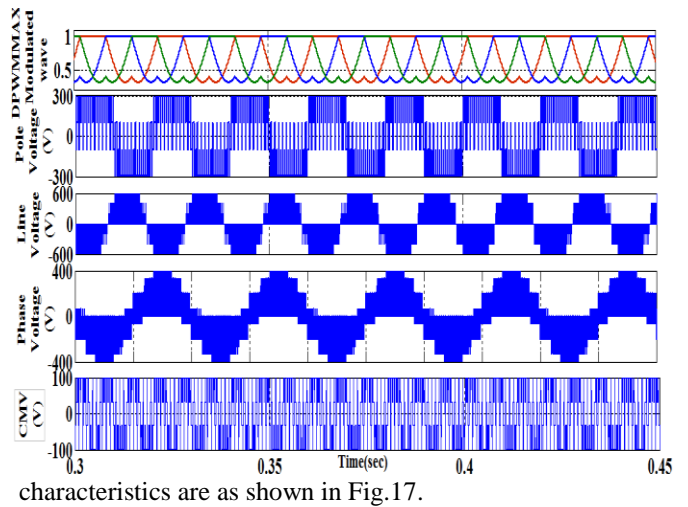


Fig.17 Modulated wave, Pole voltage, Line voltage, Phase voltage, Common mode voltage for dual inverter(Four level inverter operation with DPWMMAX control)

The performance characteristics of of dual inverter fed Induction motor drive(four level inverter operation)with DPWMMAX control i.e. Stator currents, Torque response, Speed response at no load are as shown in Fig.18 The motor achieves steady state at 0.25 sec. The Total Harmonic Distorsion(THD) for the stator currents is 3.85% for this model & the common mode voltage is mitigated compared to dual inverter fed IM drive with three level inverter operation.

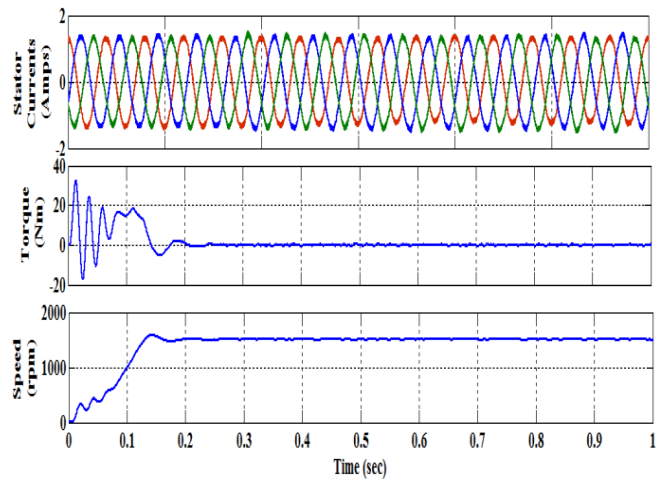


Fig.18 Performance characteristics of dual inverter (Four level inverter operation(DPWMMAX control)) fed IM drive at steady state

A dual inverter fed induction motor drive is modelled and is simulated by employing space vector pulse width modulation(DPWMMIN) control technique and the Modulated waveform, output pole voltage, Line voltage, phase voltages and the common mode voltage of the inverter which resembles the characteristics of four level inverter characteristics are as shown in Fig.19.

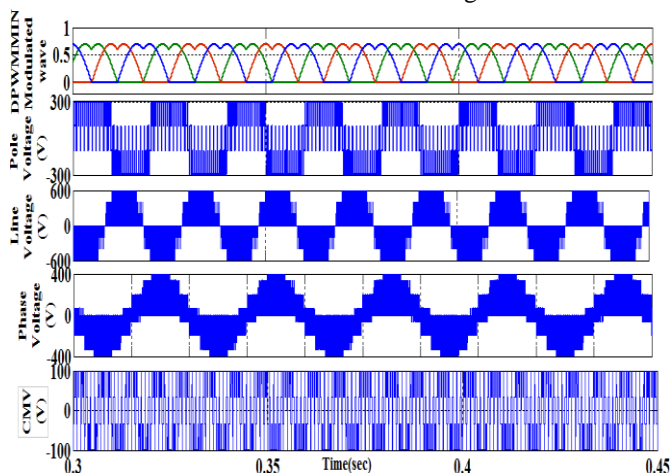


Fig.19 Modulated wave, Pole voltage, Line voltage Phase voltage, Common mode voltage for dual inverter(Four level inverter operation with DPWMMIN control)

The performance characteristics of of dual inverter fed Induction motor drive(four level inverter operation)with DPWMMIN control i.e. Stator currents, Torque response, Speed response at no load are as shown in Fig.20. The motor achieves steady state at 0.25 sec. The Total Harmonic Distortion(THD) for the stator currents is 3.43% for this model & the common mode voltage is mitigated compared to dual inverter fed IM drive with three level inverter operation.

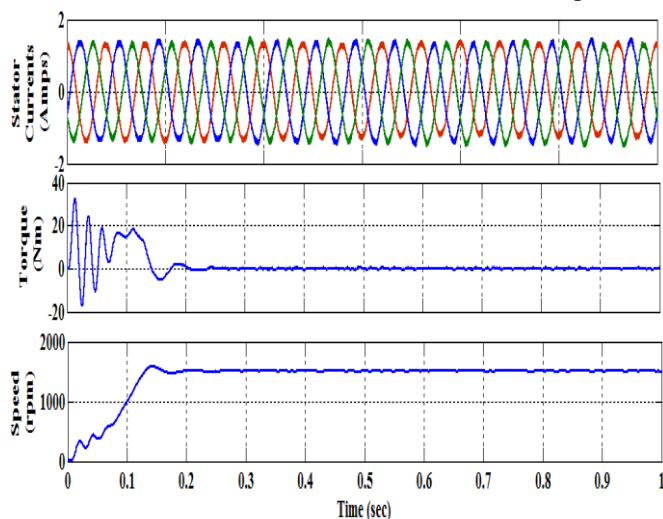


Fig.20 Performance characteristics of dual inverter (Four level inverter operation (DPWMMIN control)) fed IM drive at steady state

#### D)THD Comparison:

The THDs for stator currents of IM drive is listed out as shown in the Table.2.

Invert-er Type	Control technique	THD of stator currents of the Motor ( $I_{THD}$ )	THD of inverter voltage ( $V_{line}$ THD) In under modulation(M.I=0.8) region	THD of inverter voltage ( $V_{line}$ THD) In over modulation (M.I=1.154) region	CMV magnitude
2 level	SVPWM	7.26%	77.27%	44.11%	$=V_{dc}/2 = 300$
3 level	CSVPWM	4.77%	64.97%	22.37%	$=V_{dc}/2 = 300$
	PWMMAX	3.97%	70.09%	24.57%	
	DPWMMIN	3.85%	69.99%	23.75%	
4 level	CSVPWM	4.51%	63.65%	25.16%	$=V_{dc}/6 = 100$
	DPWMMAX	3.85%	72.15%	26.99%	
	DPWMMIN	3.43%	71.48%	25.55%	

Table.2 Comparison of stator currents THDs for various control techniques

## 4. CONCLUSION

In this paper the implementation of dual inverter fed induction motor drive has been done. With the implementation of triangular based SVPWM the machine performance will be improved in the context of harmonic spectra and effective DC bus utilization over the conventional sinusoidal pulse width modulation technique. And the zero sequence voltage problems is also mitigated at a greater level compared to other mitigating techniques. This work can be extended with the implementation of SVPWM for higher level(5,6,7 levels) for dual inverter fed open end winding induction motor.

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