Current Hormonic Analysis Of A Dual Two Level Inverter Fed Open-End Winding Induction Motor Drive Based On SVPWM Switching Stratagies

Dr. K. Sri Gowri[1], S. Venkata Mahesh[2] and M.Abdul Hakeem[3]
[1] *Professor, Dept of Electrical and Electronics Engg, RGM College of Engg & Tech, Nandyal, India.*
[2] *PG-student, , Dept of Electrical and Electronics Engg, RGM College of Engg & Tech, Nandyal, India.*
[3] *PG-student, , Dept of Electrical and Electronics Engg, RGM College of Engg & Tech, Nandyal, India*

ABSTRACT: *An open-end winding induction motor, fed by two 2-level inverters connected at either end produces space vector locations, identical to those of a conventional 3-level inverter. In this paper, two switching algorithms are proposed to implement space vector PWM for the dual inverter scheme. The proposed algorithms do not employ any look-up tables. The time consuming task of sector identification is altogether avoided in both these algorithms. The proposed algorithms employ only the instantaneous reference phase voltages for the implementation of the space vector PWM. The harmonic content of the three phase currents in the motor are analyzed with an appropriate variation in its modulation index in both the proposed algorithms and compared simultaneously. Thus the performance in terms of harmonic analysis is carried out using MATLAB/SIMULINK for an open end induction motor drive.*

***Keywords**: Dual-inverter, space vector modulation, Open-end winding induction motor*.

I. INTRODUCTION

Various PWM schemes are presented for the two-level inverters and their effects on the load are also continuously investigated. Thrive to get improved performance is on the anvil employing suitable PWM techniques [1]-[6] or using multi-level inverters. Multi-level inverters are finding increasing research opportunities and it is clearly evident in the past few years. This is due to the reduced total harmonic distortion (THD) in the output voltage and genesis of higher voltage with use of series connections of lower voltage rating switching devices. Various derivative of this power circuit and the associated PWM schemes are also reported in the recent past [6]-[14].

Two space vector modulation techniques are suggested, which obviate the need for the sector identification. Also these PWM schemes do not employ any look-up table, thus reducing the memory requirement. Fig.1 shows the basic open-end winding induction motor drive operated with a single power supply. The symbols v_{ao}, v_{bo} and v_{co} denote the pole voltages of the inverter-1.Similarly, the symbols $v_{a'o}$, $v_{b'o}$ and $v_{c'o}$ ' denote the pole voltages of inverter-2. The space vector locations from individual inverters are shown in Fig.2. The numbers 1 to8 denote the states assumed by inverter-1 and the numbers1' through 8' denote the states assumed by inverter-2[1-5]. Table-1 summarizes the switching state of the switching devices for both the inverters in all the states. In Table-1,a '+' indicates that the top switch in a leg of a given inverter is turned on and a '-' indicates that the bottom switch in a leg of a given inverter is turned on.

As each inverter is capable of assuming 8 states independently of the other, a total of 64 space vector combinations are possible with this circuit configuration .The space vector locations for all space vector combinations of the two inverters are shown in Fig.3. InFig.3, |OA| represents the DC-link voltage of individual inverters, and is equal to $V_{dc}/2$ while |OG| represents the DC-link voltage of an equivalent single inverter drive, and is equal to V_{dc}

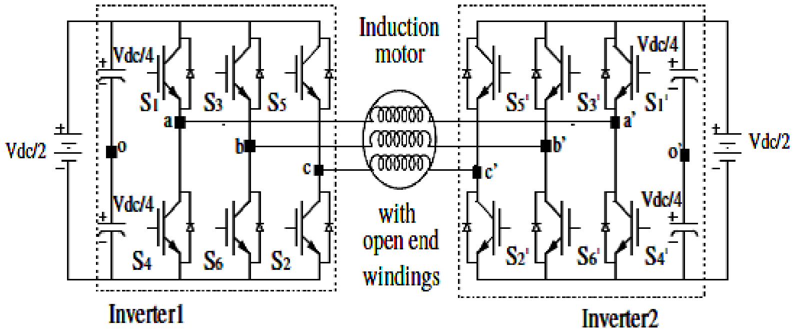

Fig.1: Power circuit configuration of dual two-level inverter

TABLE 1: Switching states of the individual inverters

state of inverter 1	*Switches turned on*	*State of Inverter-2*	*Switches turned on*
1 (+ - -)	S6, S1, S2	1' (+ - -)	S6', S1', S2'
2 (+ + -)	S1, S2, S3	2' (+ + -)	S1', S2', S3'
3 (- + -)	S2, S3, S4	3' (- + -)	S2', S3', S4'
4 (- + +)	S3, S4, S5	4' (- + +)	S3', S4', S5
5 (- - +)	S4, S5, S6	5' (- - +)	S4', S5', S6'
6 (+ - +)	S5, S6, S1	6' (+ - +)	S5', S6', S1'
7 (+ + +)	S1, S3, S5	7' (+ + +)	S1', S3', S5'
8 (- - -)	S2, S4, S6	8' (- - -)	S2', S4', S6'

The following PWM strategies are proposed in this paper:

1. The Decoupled PWM strategy
2. The Biasing inverter PWM strategy

II. DECOUPLED PWM SCHEME:

The reference voltage vector to be realized by the dual inverter is shown as V_{ref} in Fig.2. It can be resolved into two equal and opposite half components as $V_{ref}/2$ and $-V_{ref}/2$. The vector addition of the later and the former results in the generation of actual reference vector as:

$$V_{ref} = V_{ref}/2 - (-V_{ref}/2) \tag{1}$$

These individual reference voltages are synthesized separately by the two two-level inverters using SVPWM and are depicted in Fig.3 from Fig.2 & 3 it can be identified that

$$OV\angle\theta = ov_1\angle\theta\text{-}ov_2\angle(180+\theta) \tag{2}$$

The voltage vector OV_1 is synthesized by inverter-1 and OV_2 by inverter-2 respectively and are given as:

$$OV_1 = v_{a0}e^{j0} + v_{b0}e^{\frac{j2\pi}{3}} + v_{c0}e^{\frac{j4\pi}{3}} \tag{3}$$

$$OV_2 = v_{a'0}e^{j0} + v_{b'0}e^{\frac{j2\pi}{3}} + v_{c'0}e^{\frac{j4\pi}{3}} \tag{4}$$

where v_{ao}, v_{bo}, v_{co} are three-phase pole voltages of inverter-1 and $v_{b'o}$, $v_{b'o}$,$v_{c'o}$ are three-phase pole voltages of inverter-2 The actual vector can now obtained using the vectors defined in eqns.(3) & (4) as:

$$OV = V_{aa'}e^{j0} + V_{bb'}e^{\frac{j2\pi}{3}} + V_{cc'}e^{\frac{j4\pi}{3}} \tag{5}$$

$$V_{aa'} = V_{ao} - V_{a'o} \tag{6}$$
$$V_{bb'} = V_{bo} - V_{b'o} \tag{7}$$
$$V_{cc'} = V_{co} - V_{c'o} \tag{8}$$

Where $v_{aa'}$, $v_{bb'}$, $v_{cc'}$ are the three-phase phase voltages of the dual-inverter fed induction motor drive.

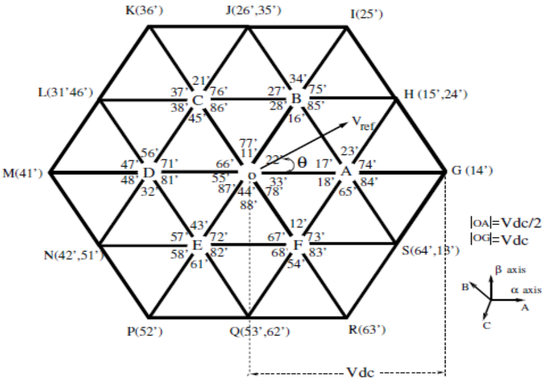

Fig.2: Space vector locations of dual two-level inverter

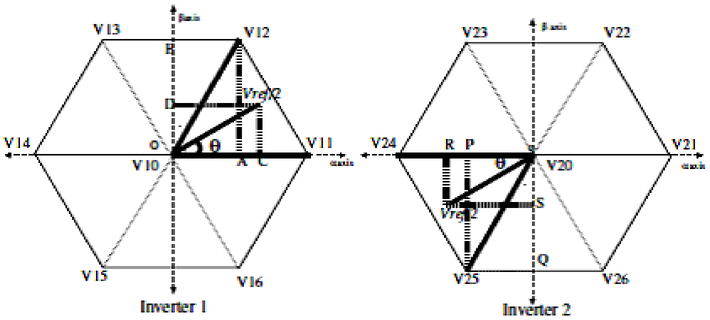

Fig.3: Principle of decoupled PWM technique and switching voltage vector, reference voltage vector projection on α and β axis

In Fig.3, the switching vectors V_{1x}, V_{2x} (x=0, 1, 2, 3, 4, 5, 6) for inverter-1 & 2 can be identified and are defined as:

$$V_{1x} = \frac{2}{3} V_{dc} (S_{A1} + S_{B1} e^{\frac{j2\pi}{3}} + S_{C1} e^{\frac{j4\pi}{3}}) \tag{9}$$

$$V_{2x} = \frac{2}{3} V_{dc} (S_{A2} + S_{B2} e^{\frac{j2\pi}{3}} + S_{C2} e^{\frac{j4\pi}{3}}) \tag{10}$$

The reference voltage vector (V_{ref} in Fig.2) is situated at an angle Θ w.r.t the α-axis. The references to the individual inverter would then be $V_{ref}/2$ where one is at angle 'Θ' while the other is at an angle '180+Θ' both measured w.r.t the β-axis (Fig.3).The respective references are synthesized by the inverters and the switching vectors for inverter-1 can be identified as V_{11}, V_{12} &V_{10} and V_{24}, V_{25}&V_{20} for inverter-2 (Fig.3)

With the decoupled SVPWM technique, the reference vector V_{ref} is decoupled into two equal halves as described in the previous section. These space vectors are shown in Fig.3 and are said to fall in sector 1 (for inverter-1) and sector 4 (for inverter-2). With inverter-1 and 2, the space vectors $V_{ref}/2$,$-V_{ref}/2$ respectively are realized in the average sense using three nearest voltage vectors of the sector in which the tip of reference vector lies. To realize $V_{ref}/2$, inverter-1 switches between vectors V_{10}, V_{11}, V_{12}, V_{17} with timing intervals of $T_{10}/2$, T_{11}, T_{12}, $T_{17}/2$ respectively for the center-spaced PWM . Similarly, inverter-2 switches between V_{20}, V_{24}, V_{25}, and V_{27} with timing intervals of $T_{20}/2$, T_{24}, T_{25}, and $T_{27}/2$ respectively.

III. RESULTS & DISCUSSIONS FOR THE DECOUPLED PWM STRATEGY

The dual two-level inverter with decoupled SVPWM switching scheme feeding power to open end winding induction motor drive is simulated using Matlab/SIMULINK simulation software. Then the results are verified experimentally. A total of 48 samples is chosen in the entire work covering one cycle of the output voltage, irrespective of the modulation index of the drive (speed of the motor).

The gating pulses of the top switching devices of the individual inverters (depicting the timings T_{ga}, T_{gb}, T_{gc} for invrter-1 and $T_{ga'}$, $T_{gb'}$, $T_{gc'}$ for inverter-2) are shown in Fig.4 . The three phase pole voltages of the individual inverters will be a replica of the gating pulses shown in Fig.6 except for their voltage levels.

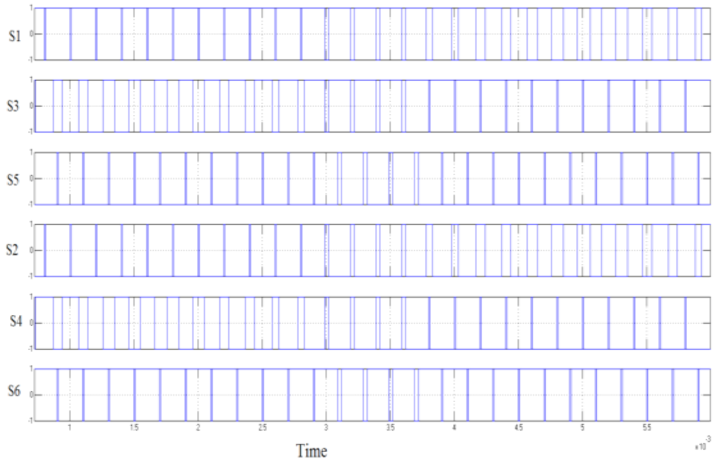

Fig.4: Gating Pulses for Inverter-1(Tga,Tgb,Tgc) and Inverter-2(Tga',Tgb',Tgc') for the modulation index 0.75

Here, the modulation index is defined as the ratio of the length of the reference space vector (V_{ref}) and the DC-bus voltage (V_{dc}).The experimentally obtained a-phase pole voltages of the two inverters, difference in a-phase pole voltages, motor a-phase voltage and the motor a-phase no-load current for a modulation index of 0.75 are as shown in the fig(5).

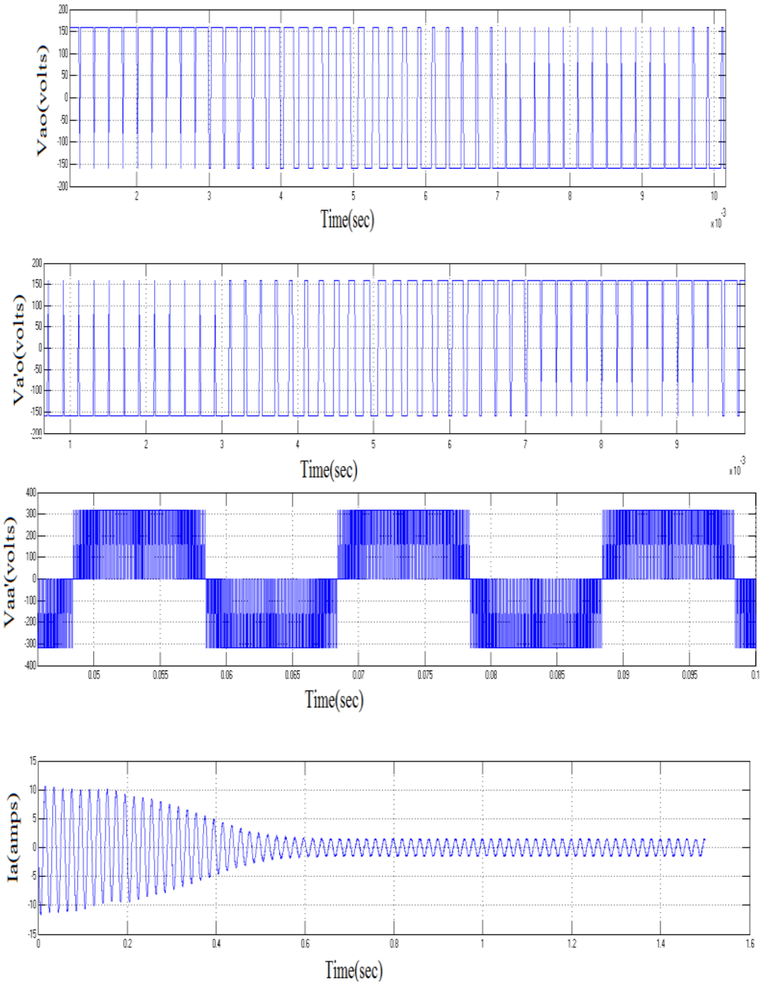

Fig.5: Simulated pole voltages of inverter-1 and inverter-2 (Top 2 traces), Difference in a-phase pole (Vaa′) voltages (3rd trace), motor a-phase current (4th trace), for a modulation index of 0.75.

IV. THE BIASING INVERTER PWM STRATEGY

This PWM strategy is based on the observation that the space vector combinations at the vertices and the center of a given sub-hexagon are obtained by clamping one inverter with an active state, while the other inverter assumes all the eight states. Consequently, one inverter may be employed as the biasing inverter to realize the biasing vector and the other inverter may be switched around this biasing vector. Figure 6 shows the basic operating principle of this PWM strategy.

In Fig 6, **OT** represents the reference vector with its tip situated in sector-7. It is resolved into two components **OA** and **AT**. The vector **OA** may be output with inverter-1 with its state clamped at 1(+--, Table-1) throughout the sampling time interval. The vector **AT** is realized in the average sense by switching inverter-2 around the sub hexagonal center, A. Alternatively, the biasing vector **OA** may be output with inverter-2 with its state clamped at 4'(-++, Table-1) throughout the sampling time interval. In that case, the switching vector **AT** is generated with inverter-1.

The modified instantaneous voltage phase references corresponding to the switching vector **AT** are denoted by V_a ,V_b and V_c obtained by the following procedure:

1. The instantaneous phase references Va* ,*Vb** and Vc* corresponding to the reference vector **OT** are transformed into the corresponding equivalent two-phase system references Vα* and Vβ* using the classical three phase to two phase transformation given by:

$$\begin{bmatrix} v_\alpha^* \\ v_\beta^* \end{bmatrix} = \begin{bmatrix} \frac{3}{2} & 0 & 0 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a^* \\ v_b^* \\ v_c^* \end{bmatrix}$$

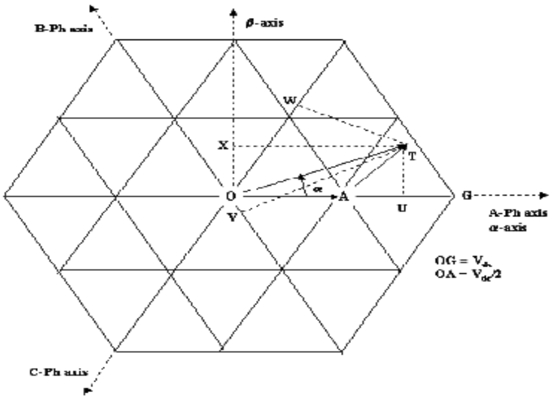

Fig.6: Principle of biasing inverter PWM strategy

2. The sub-hexagonal center situated nearest to the tip of the reference vector **OT** is then determined.

3. The coordinates of the nearest sub-hexagonal center in the V_α-V_β plane (the point 'A' in this example, Fig.26), denoted as $V_{\alpha,nshc}$ and $V_{\beta,nshc}$ are known for all the six sub-hexagonal centers. For example, the coordinates of the point 'A' in the V_α-V_β plane are given by $(V_{dc}/2,0)$.

4. Since the vector **OA** is output by the biasing inverter, the coordinates of the switching vector (**AT** in the present case) denoted as $V_{\alpha,sw}$ and $V_{\beta,sw}$ are given
   $V_{\alpha,sw} = V_\alpha^* - V_{\alpha,nshc}$ and $V_{\beta,sw} = V_\beta^* - V_{\beta,nshc}$

5. The modified reference phase voltages V_a ,V_b and V_c for the switching inverter are then obtained by transforming $V_{\alpha,sw}$,$V_{\beta,sw}$ into the corresponding three phase variables by using the classical two phase –three phase transformation given by:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} 2/3 & 0 \\ -1/3 & 1/\sqrt{3} \\ -1/3 & -1/\sqrt{3} \end{bmatrix} \begin{bmatrix} V_{\alpha,sw} \\ V_{\beta,sw} \end{bmatrix}$$

6. If inverter-2 is employed as the biasing inverter, the modified references are used directly to generate the switching vector **AT** with inverter-1. On the other hand, if inverter-1 is used as the biasing inverter, it is obvious that the modified references must be negated to generate the switching vector **AT** with inverter-2.

V. RESULTS & DISCUSSIONS FOR THE BIASING INVERTER PWM STRATEGY

The dual two-level inverter with biasing SVPWM switching scheme feeding power to open end winding induction motor drive is simulated using Matlab/SIMULINK simulation software. Then the results are verified experimentally.. A DC-bus voltage of 200 volts is chosen to run the drive and V/f control is maintained in the entire speed range of the induction motor. A total of 48 samples is chosen in the entire work covering one cycle of the output voltage, irrespective of the modulation index of the drive (speed of the motor).

The gating pulses of the top switching devices of the individual inverters (depicting the timings T_{ga}, T_{gb}, T_{gc} for invrter-1 and $T_{ga'}$, $T_{gb'}$, $T_{gc'}$ for inverter-2) are obtained simultaneously shown in Fig.7.The three phase pole voltages of the individual inverters will be a replica of the gating pulses shown in Fig.8 except for their voltage levels.

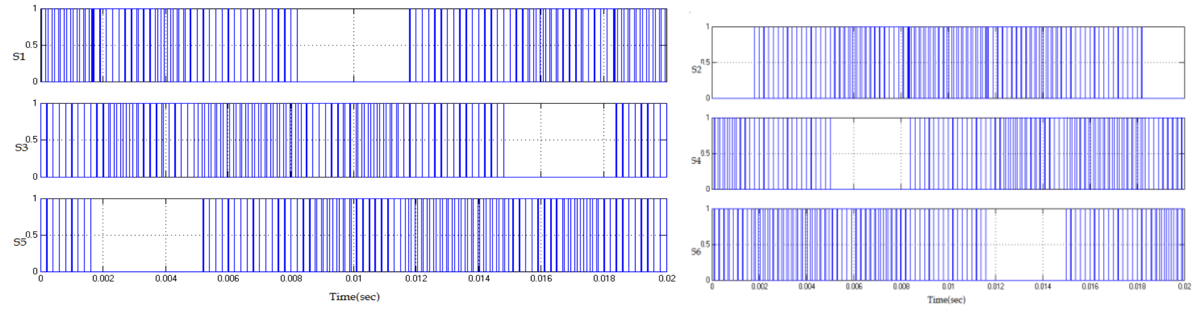

Fig.7: Gating Pulses for Inverter-1(Tga,Tgb,Tgc) and Inverter-2(Tga',Tgb',Tgc') for the modulation index 0.75

Here, the modulation index is defined as the ratio of the length of the reference space vector (V_{ref}) and the DC-bus voltage (V_{dc}).The experimentally obtained a-phase pole voltages of the two inverters, difference in a-phase pole voltages, motor a-phase voltage and the motor a-phase no-load current for a modulation index of 0.75 are as shown in the fig(8).

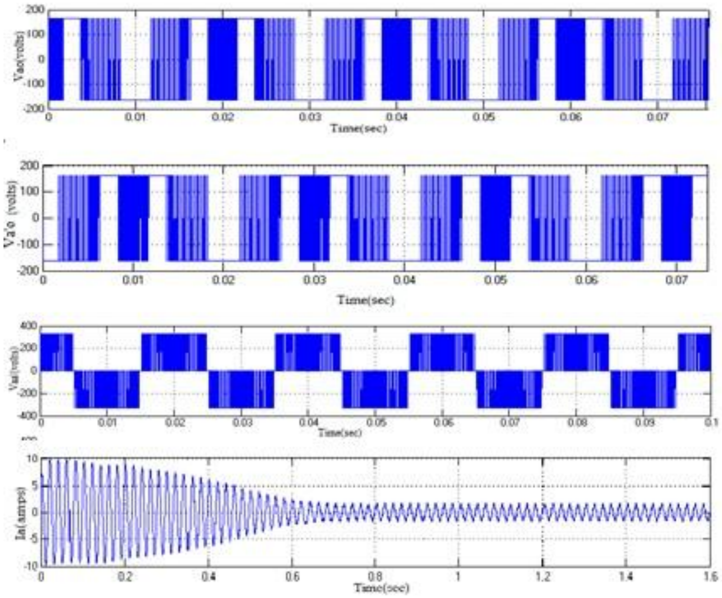

Fig. 8: Simulated pole voltages of inverter-1 and inverter-2 (Top 2 traces), Difference in a-phase pole (Vaa′) voltages (3rd trace), motor a-phase current(4th trace), for a modulation index of 0.75.

The comparison in terms of harmonic content for both the cases when the motor is fed by decoupled inverter and biasing inverters is done by the total harmonic distortion along with the respective change in the corresponding modulation index. For instance the simulated results of harmonic distortion for both the cases for a modulation index of 0.75 are as shown in fig (9).

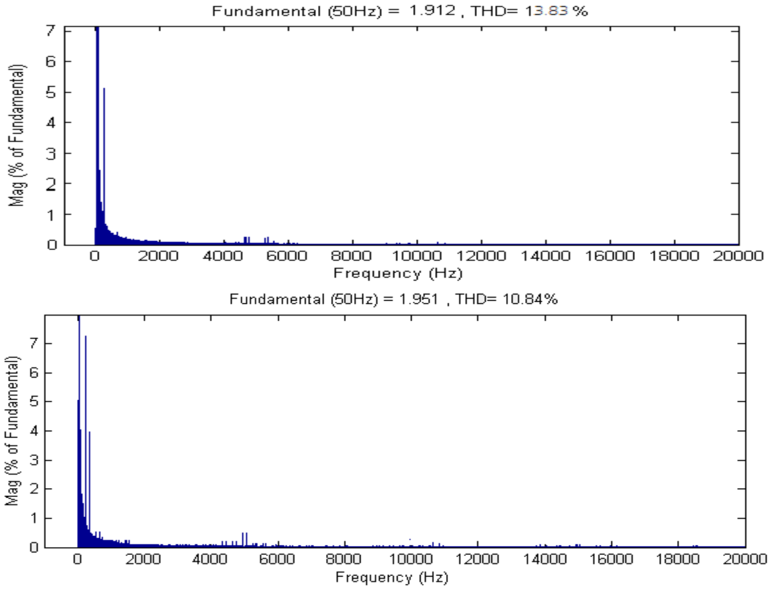

Fig. 9: Simulated Results Of %THD for Decoupled inverter fed (Top trace) and Biasing inverter fed (Bottom trace) Induction motor drive for a modulation index of 0.75

Various changes in the %THD at different levels of Modulation index are presented in table (2).With this it is reiterated that as the modulation index increases, the harmonic content in the motor phase currents is reduced.

Table (2): Total Harmonic Distortion of line currents of the induction motor for different modulation index

S.No	Operating Frequency	Modulation Index	Decoupled SVPWM Inverter Fed Induction Motor Drive Phase Current(I_a) % THD	Biasing SVPWM Inverter Fed Induction Motor Drive Phase Current(I_a) % THD
(1)	50	0.1	16.55	14.26
(2)	50	0.2	16.47	14.01
(3)	50	0.4	14.29	13.19
(4)	50	0.75	13.83	10.84
(5)	50	0.9	8.57	8.28

VI. CONCLUSION:

The dual two-level inverter is capable of generating three level output voltage using the SVPWM switching schemes. With the biasing inverter PWM strategy the reference space vector is reproduced in the average sense by switching amongst the vector combinations available at the nearest three vertices. Consequently the switching ripple with this strategy is lesser than the decoupled PWM strategy.The rms value of this harmonic content is decreasing with the increase in the modulation index of the dual-inverter feeding the open-end winding induction motor. In Biasing inverter PWM strategy,THD of the motor phase currents is low compared to that of Decoupled PWM algorithm.

APPENDIX:

Specification Parameters Of Induction Motor:

Stator Resistance (Rs) =7.83Ω
Rotor Resistance (Rr) =7.55Ω
Stator Inductance (Ls) =0.4751H
Rotor Inductance (Lr) =0.4751H
Mutual Inductance (Lm) =0.4535H
Moment Of Inertia (J) =0.06
Poles=4

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