A Novel Modulation Scheme for a Six Phase Induction Motor with Open-End Windings

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Abstract: A modulation scheme for a six phase induction motor is presented in this paper. For a six phase induction motor drive harmonics of the order 6n ±1(n=1,3,5 etc.,) will not contribute to the air gap flux and hence these harmonic currents are limited by the stator impedance only. So harmonic filters are needed for the suppression of these (6n ±1(n=1,3,5 etc.,)high amplitude harmonic currents, when a six phase induction motor is used for variable speed application. In the proposed scheme, a modulation technique to eliminate the 6n ±1(n=1,3,5 etc.,) harmonic currents, without the need for harmonic filters, from the stator phases of a six phase induction motor drive is explained. An open -end winding drive configuration with DC link voltages, chosen in such away that a 12-sided polygonal voltage space phasor combinations are achieved for each 3-phase group, independently. A modulation scheme based on12-sided polygonal voltage space phasors will cancel the 6n ±1(n=1,3,5 etc.,) harmonic voltages from all the motor phases and hence currents due to these harmonics will not flow in the motor phases of the six phase machine. The proposed drive scheme is experimentally verified, for variable speed application, using a1HP six phase induction motor drive.

1.INTRODUCTION

Six phase or split-phase induction motor drive with isolated neutral for the two sets of three phase windings will have high amplitude 5^{th} and 7^{th} harmonic currents in the stator [1] [3]. But these harmonics (6n ± 1, n=1,3,5 etc.,) will not contribute to the air gap flux, as the flux produced by these harmonics gets cancelled due to the winding disposition of the two sets of 3-phase windings. Zhao and Lipo proposes a space phasor based PWM technique to suppress the 5^{th} and 7^{th} harmonic currents, but with increased inverter switchings in a sampling interval [4]. Kuniomi Oguchi et.al proposes a 60 step motor phase voltage waveform for a six phase machine , by cascading a single phase 3-level inverter with two 2-level inverters[5]. Here, the PWM technique suppress the higher order harmonics and the 5^{th} and 7^{th} order harmonics (6n ± 1, n=1,3,5 etc.,) are suppressed by harmonic filters [2] [5]. Conventional 3phase induction motor with open-end winding drive (motor is fed from both the ends by two 2-level inverters) produces voltage space phasor locations similar to a 3-level inverter [6] [7]. Thus with inverter fed induction motor drive with open-end winding configuration, the low order voltage harmonics can be suppressed, when compared to a single 2-level inverter drive. The open- end winding drive concept is extended in this paper for the six phase or split phase induction motor drive, for cancelling the 6n ± 1, n=1,3,5 etc., harmonic voltage from the motor phases. The split-phase motor is fed from both the ends from 2-level inverters with asymmetrical DC link voltages, so that a 12 sided polygonal voltage space phasor locations are possible from the drive for PWM control.

II. OPEN-END WINDING SPLIT PHASE INDUCTION MOTOR DRIVE

The winding disposition for the split phase induction motor is shown in Fig.1a. The split phase or the six phase stator structure can be obtained by splitting the phase belt of a conventional 3-phase induction machine into two halves with a 30^0 electrical separation [3].The six phase voltage and currents can be analysed by the following vector[4].

$$S_k(\omega t) = [\cos k(\omega t)\ \ \cos k(\omega t-\theta)\ \ \cos k(\omega t-4\theta)\ \ \cos k(\omega t-5\theta)\ \ \cos k(\omega t-8\theta)\ \ \cos k(\omega t-9\theta)] \quad (1).$$

Where θ =30° and $k = 1,3,5,...$ denotes the harmonic order. Each harmonic vector spans a surface in the original six – dimensional space. The various harmonics can be grouped into three groups. The harmonics of the order 6n ± 1,n=0,2,4,etc., span a subspace-S_1 in the original six-dimensional space and the orthogonal co-ordinates for this subspace can be written by selecting $\omega t = 0$ *and* $(\pi/2)$

$$\begin{aligned}\alpha_1 &= [1\ \ \cos\theta\ \ \cos(4\theta)\ \ \cos(5\theta)\ \ \cos(8\theta)\ \ \cos(9\theta)] \\ \beta_1 &= [0\ \ \sin\theta\ \ \sin(4\theta)\ \ \sin(5\theta)\ \ \sin(8\theta)\ \ \sin(9\theta)]\end{aligned} \quad (2).$$

Similarly the harmonics of the order 6n ± 1,n=1,3,5,etc., span a different subspace-S_2 in the original six dimensional space. The corresponding orthogonal axes are

$$\begin{aligned}\alpha_2 &= [1\ \ \cos 5\theta\ \ \cos(8\theta)\ \ \cos(\theta)\ \ \cos(4\theta)\ \ \cos(9\theta)] \\ \beta_2 &= [0\ \ \sin 5\theta\ \ \sin(8\theta)\ \ \sin(\theta)\ \ \sin(4\theta)\ \ \sin(9\theta)]\end{aligned} \quad (3).$$

The triplen order harmonics span a different subspace-S_3 in the six dimensional space and the orthogonal vectors are

$$\begin{aligned}\alpha_3 &= [1\ 0\ 1\ 0\ 1\ 0] \\ \beta_3 &= [0\ 1\ 0\ 1\ 0\ 1]\end{aligned} \quad (4).$$

It can be shown that the subspaces S_1, S_2, S_3 are orthogonal to each other[4],i.e.

$$S_1 \bullet S_2^T = S_1 \bullet S_3^T = S_3 \bullet S_2^T = 0 \quad (5).$$

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From eqn.3 it can be verified that the fundamental components and the harmonics of the order,11,13, 23,25 etc.,are transformed into the S_1-subspace. From eqn.4, it can be noted that the harmonics of the order, 5,7,17,19,etc., are mapped into subspace-S_2,which is orthogonal to the subspace-S_1 and hence will not contribute to the rotating air-gap flux and electromechanical energy conversion [3] [4]. Since these harmonics ($6n\pm1$,n=1,3,5,etc) will not contribute to the rotating air-gap flux,, the amplitudes of these harmonics are limited only by the stator leakage impedance. Hence a substantial amount of high amplitude harmonics currents of the order $6n\pm1$,n=1,3,5,etc will flow in the stator ,unless they are suppressed by harmonic filters[1] [2].

The six phase machine phasor schematic is shown in Fig.1a. If such a machine is fed by two 2-level inverters for each 3-phase groups , the inverter voltage vectors in the subspace -S_1 is as shown in Fig. 1b[4]. The vector position -11' indicates that the inverter for the phase group – A B C is in state-1(+ - -) and also the inverter for the phase group-A' B' C' is also in state-1(+ - -)[3] [4]. The same inverter states spanning the subspace-S_2 , are as shown in Fig.1c[4]. Now in order to cancel the $6n\pm1$,n=1,3,5,etc harmonic currents (spanning the subspace-S_2) from the motor stator phases an open-end winding scheme of Fig.1d is proposed in this work. The two sets of 3phase stator groups neutral are disconnected and fed from the neutral side also, by two other inverters with isolated DC link. The DC link voltage and the space vector switching strategy for the inverters are chosen in such a way that, in each phase group the fundamental component and harmonic (spanning the subspace-S_1) should get added and the $6n\pm1$,n=1,3,5,etc harmonic currents (spanning the subspace-S_2) should get cancelled in each phase group.

Fig.1b shows the inverter vector states (spanning the subspace-S_1) for the six phase machine with neutral connected [3] [4]. Here two sets of 3-phase group are fed from two 2-level inverters with a DC link voltage (V_{DC}) of $\frac{V_D}{2\cos 15^0}$ each, (where V_D is the equivalent conventional 2-level single inverter drive with the split phase or six phase group connected as one 3-phase winding)[3]. This will result in a resultant space vector magnitude of V_D for the combined vector state 11'. Now if we choose the combined inverter vector state –53' for the inverters, the resultant vector is opposite to the combined vector state 11' in the subspace-S_1. In Fig.1c, it can be noted that these set of combined inverter states lie on the same side (same line) in the subspace-S_2. So if we choose the inverter switching state 11' for the inverter-1 and inverter-4 respectively, and inverter vector states -53' for the inverter-2 and inverter-3, (feeding from the opposite ends , with appropriate DC link magnitude-Fig.1d), the fundamental component and harmonics spanning the subspace-S_1 get added and the harmonic components $6n\pm1$,n=1,3,5,etc, spanning the subspace-S_2 get totally cancelled.

From Fig.1b the voltage space vector amplitude for the 11' inverter (inverter-1 and invert-4) switching states spanning subspace-S_1 is $= V_D$ (6).

Amplitude of the voltage space vector (Fig.1c) for the 11' inverter switching states (inverter-1 and inverter-4) in the subspace-S_2 is $= 0.267\ V_D$ (7).

Now in order to cancel this vector state in the subspace-S_2,the inverter-2 and inverter-3 need to be switched with switching state 53', with appropriate DC link voltage(Fig.1b and Fig.1c). If V_{DC} is the DC link voltage then the switching vector state 53' will have a magnitude of 0.73 V_D in the subspace-S_2(Fig.1c.). So the DC link voltage (V_{dc}) needed for the inverter-2 and inverter-3 of Fig.1d is

$$0.267\ V_{DC} = 0.73\ V_{dc} \quad (8).$$

So, $V_{dc} = 0.366\ V_{DC}$ (9).

Similar inverter switching vector states (for the cancellation of $6n\pm1$,n=1,3,5,etc harmonics) for the four inverters can be identified for a cycle of operation and the combined inverter switching vector states and its amplitude are shown in Fig.1e. From Fig.1e, it can be noted that the maximum voltage space vector magnitude from the total drive system is

$$1.233\times 2V_{DC} \quad =2.446\ V_{DC} \quad (10).$$

But $V_{DC} = \frac{V_D}{2\cos 15^0}$, and hence the resultant voltage vector magnitude from the combined system (Fig1d and Fig.1f) is

$$\frac{2.446\,V_D}{2\times 0.9659} = 1.266.V_D \quad (11)$$

So in order to have identical resultant voltage vector magnitude (V_D) for the 3-phase system as well as the proposed six phase system, The DC link Voltage (V_{DC}) needed for the Inverter-1 and Inverter-4 is (Fig.1d) = 0.41 V_D and for the lower voltage inverters(inverter-2 and inverter-3) the DC link voltage (V_{dc}) needed is 0.15 V_D, where V_D is the DC link voltage needed for the drive when the six phase machine is run as a 3-phase machine , by appropriately connecting the split phase groups [3].

Both the neutral of the 3-phase winding groups are disconnected and fed from both the ends, by two 2-level inverters with a DC link voltage ratio of 1: 0.366 (Fig.1d). From Fig.1d it can be seen that the high voltage inverters (inverter-1 and inverter-4) are connected from the same DC link supply and the low voltage DC link inverters are isolated with separate DC link sources. This isolation is needed to suppress the triplen harmonic currents from the motor phases. The voltage space phasors (reference α- axis is placed along the motor A-phase axis) from all the four inverters are presented in Fig.1e. The 12-sided voltage space phasor combination from inverter-1 and inverter-2 (Fig.1e) driving the open – end winding 3-phases A, B, C and that for the A', B', C' phases (from inverter-3 and inverter-4) are shown in Fig.1e. From Fig.1e it can be noted that both the 12- sided voltage space phasor combinations from the inverters for the two 3-phase groups have a magnitude of $1.223V_{DC}$ and the voltgae space phasor combinations from the A' B' C' group is 30^0 lagging with respect to that of the A B C group according to the winding disposition (Fig.1a). A PWM scheme using the 12-sided polygonal space vector voltage is implemented for the present drive. By using the 12-sided polygonal voltage space vectors, for voltage control of the 3-phase groups, where all the $6n \pm 1$, n=1,3,5 etc., harmonics can be totally eliminated from the individual motor phases [3] [4].

III. EXPERIMENTAL RESULTS

The inverter pole voltages for a 12-step operation (for inverter switching sequence- Fig.1e) is presented in Fig.1f and the corresponding motor A- phase voltage is shown in Fig.2a (experimental results from a 1HP split-phase induction motor drive). The harmonic spectrum of the phase voltage shows absence of all the $6n \pm 1$, n=1,3,5 etc.,harmonics (Fig.2b). The next higher order harmonics are the 11^{th} and13^{th} (Fig.2b). The motor phase-A and phase-C' currents at no-load operation is shown in Fig.2c. The drive is operated with pole voltage waveforms of Fig.2d with an extra addition of 3.75^0 symmetrical notches for the 11^{th} and13^{th} harmonic suppression (Fig.2d). The motor phase- A and A' voltage waveforms (30^0 separated) with 11^{th} and13^{th} suppression is presented in Fig.2e. The harmonic spectrum of Fig.2f shows a 50% and 30% reduction in 11^{th} and13^{th} harmonic voltages when compared to Fig.2b. The corresponding motor phase currents (phase-A and C' with 90^0 phase shift) are shown in Fig.2g. The drive is operated with variable speed and the PWM is achieved by comparing the pole voltage wave forms (with notches to suppress the 11^{th} and 13^{th} harmonics - Fig.2d) with a triangular carrier wave with frequencies 12f, 24f and 48f. Fig.2e to Fig.2m shows the motor phase voltages and phase currents at different modulation indices. The motor phase current waveforms clearly shows the absence of $6n \pm 1$, n=1,3,5 etc., harmonics. The harmonic amplitudes of motor phase voltages as a ratio to the DC link voltage V_{DC} is computed and plotted against modulation index in Fig.3a, Fig.3b and Fig.3c for triangular carrier frequencies 12f, 24f and 48f (f- is the fundamental motor frequency). All the waveforms shows the absence of the $6n \pm 1$, n=1,3,5 etc., harmonics from the phase voltage waveforms. For carrier frequency of 24f amplitude harmonics will be shifted to 47f and 49f and with triangular carrier frequency of 48f the high amplitude harmonics will be shifted to 94f and 95f. With modulating waves shown in Fig.2d, a smooth transition up to modulalion index-1 is possible in the present drive, with highly suppressed 11^{th} and 13th order harmonics, and at the same time eliminating the $6n \pm 1$, n=1,3,5 etc., harmonics.

IV. CONCLUSION

An open – end winding drive scheme for a six phase or split phase induction motor is proposed in this paper. The two sets of 3- phase group is fed by two 2-level inverters with DC link voltage ratio of 1:0.366. Each 3-phase group produces a 12-sided polygonal voltage space phasors and the two groups of 12-sided polygonal space phasors are 30^0 phase shifted. If V_D DC link voltage of a conventional 2-level inverter fed 3-phase IM drive, for identical flux operation, $0.41V_D$ DC link voltage for the high voltage inverters (Inverter-1 and inverter-4 of fig.1b) and $0.366\times 0.41V_D = 0.15V_D$ for the low voltage inverters (inverter-2 and inverter-3, Fig.1b) are only needed for the split–phase induction motor drive with open – end windings (Fig.1a and Fig.1b). A linear modulation scheme up to the rated speed for the six phase induction motor is proposed, in which all the $6n \pm 1$, n=1,3,5 etc harmonics are eliminated (without the need for harmonic filters), and also the 11^{th} and 13^{th} are suppressed, from the motor phase voltages. By appropriately choosing the frequency of the triangular carrier wave (12f, 24f, 48f etc.,) at different speed range the inverter switching frequencies can be limited around 600Hz.

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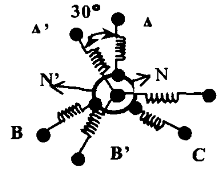


Fig. 1a Split-phase induction motor (winding connections)

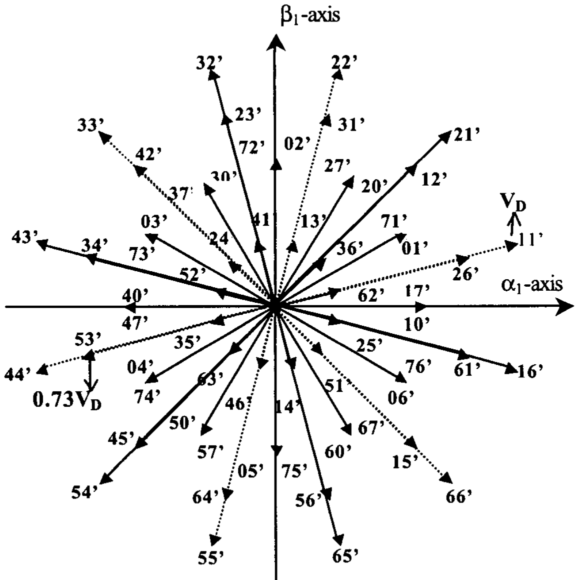


Fig. 1b Inverter voltage vectors projected on S_1 - plane., (neutral connected six phase induction motor drive.)

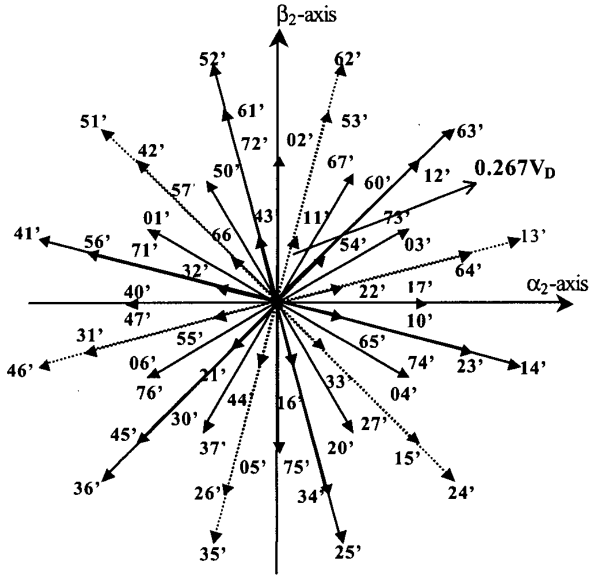


Fig. 1c Inverter voltage vectors projected on S_2 - plane, (neutral connected six phase induction motor drive.)

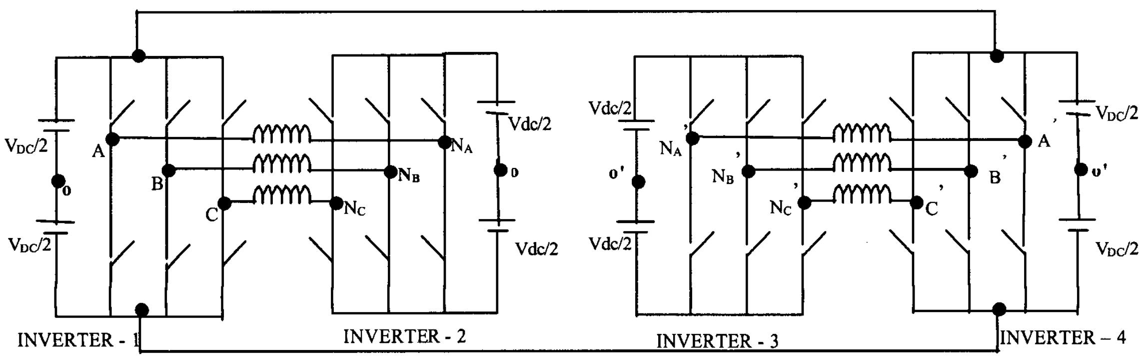


Fig. 1d Schematic of power circuit for the proposed scheme. Vdc = 0.366 V_{DC}

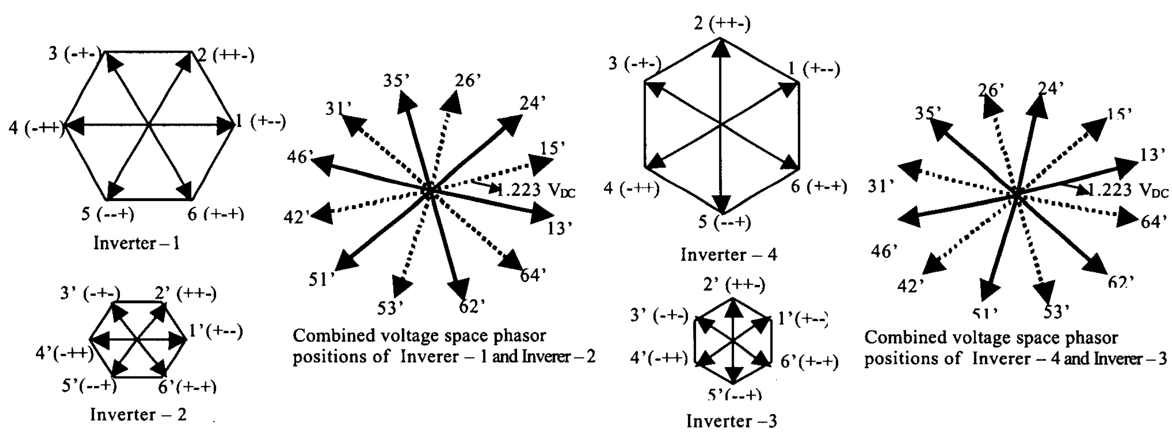


Fig. 1e Voltage space vectors of individual inverters (For inverter - 1 and inverter – 4, vector magnitude = V_{DC}, and for inverter - 2 and inverter – 3, vector magnitude = Vdc) and voltage space vectors of combination of inverters.

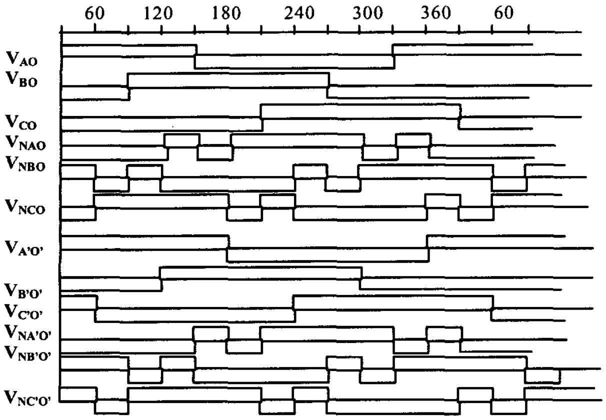


Fig. 1f Pole voltage (V_{AO}, V_{BO}, V_{CO}) of inverter-1
Pole voltage (V_{NAO}, V_{NBO}, V_{NCO}) of inverter-2
Pole voltage ($V_{A'O'}$, $V_{B'O'}$, $V_{C'O'}$) of inverter-4
Pole voltage ($V_{NA'O'}$, $V_{NB'O'}$, $V_{NC'O'}$) of inverter-3

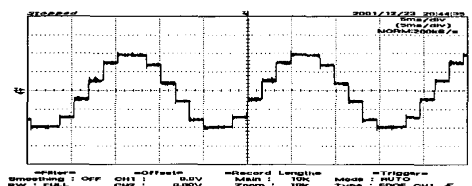


Fig.2a Phase voltage.- Modulation index = 1.0
(Over-modulation). Y-axis75V/div,X-5ms/div

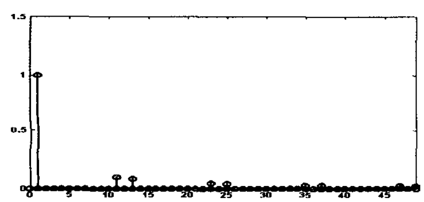


Fig.2b –Fourier spectrum of phase voltage of Fig.2a.

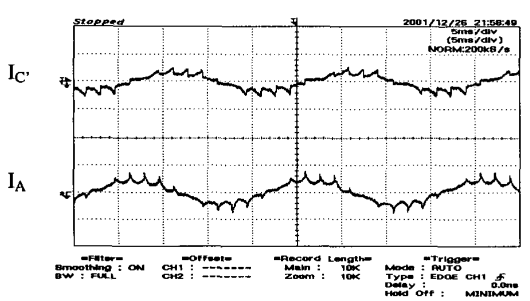
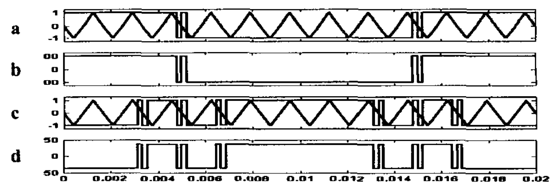


Fig.2c – Phase-A and Phase-C' currents - at no load.
Modulation index = 1.0 , Y-axis 2amp/div



a – Modulating wave (11[th] and 13[th] harmonics suppressed) and triangle carrier wave (inverter-1)
b – Inverter-1 pole voltage- Phase A
c – Modulating wave (11[th] and 13[th] harmonics suppressed) and triangle carrier wave (inverter-2)
d – Inverter-2 pole voltage- Phase –NA'

Fig.2d Modulating wave and triangular carrier wave (over modulation) **fc/f = 12.**

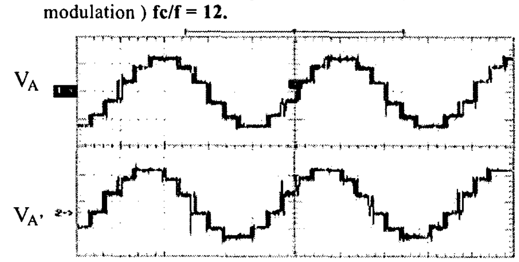


Fig.2e – Phase voltage V_A and $V_{A'}$ in phase – A and phase – A' respectively. .(with 11[th] and 13[th] suppression)
Modulation index = 1.0 –Y axis-100V/div, X-5ms/div

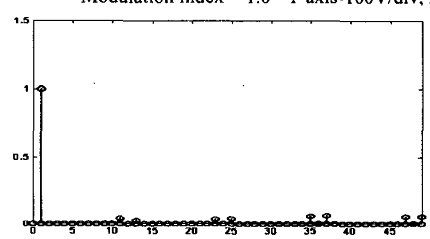


Fig.2f –Fourier spectrum of phase voltage of Phase-A of Fig.2e.(with 11[th] and 13[th] suppression)

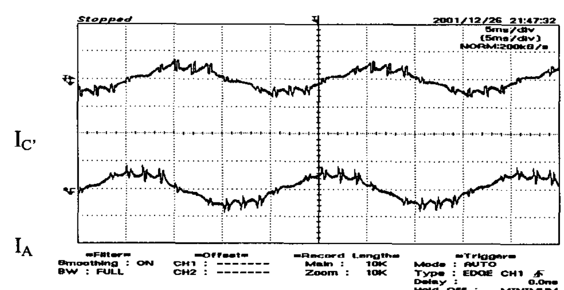


Fig.2g – Phase-A and Phase-C' currents - at no load. (with 11[th] and 13[th] suppressed)
Modulation index = 1.0 , Y-axis 2amp/div

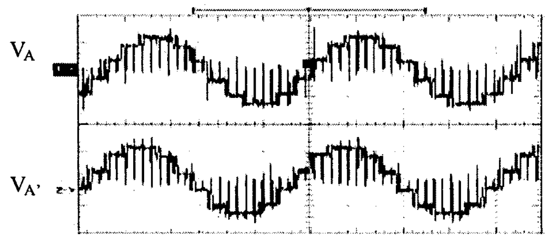


Fig.2h – Phase voltage V_A and $V_{A'}$.(with 11th and 13th suppression) Modulation index = 0.9 , **fc/f = 12** Y-axis100V/div, X-axis5ms/div

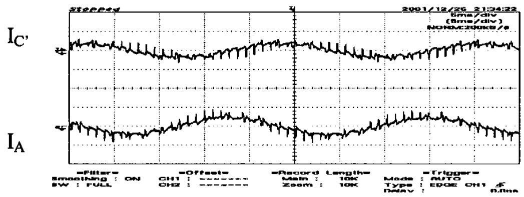


Fig.2i – Phase current I_A and $I_{C'}$ at no load .(with 11th and 13th suppression) Modulation index = 0.9 , **fc/f = 12** Y-axis 1amp/div, X-axis 5ms/div

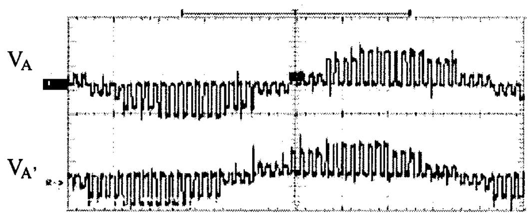


Fig.2j – Phase voltage V_A and $V_{A'}$ . .(with 11th and 13th suppression) Modulation index = 0.45 , **fc/f = 24** Y-axis 100V/div, X-axis 5ms/div

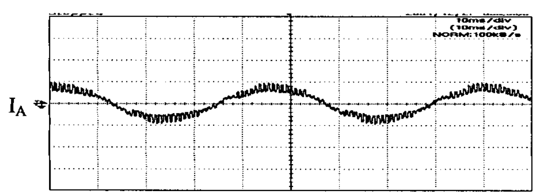


Fig.2k – Phase current I_A in phase – a.(with 11th and 13th suppression) Modulation index = 0.45 , **fc/f = 24**

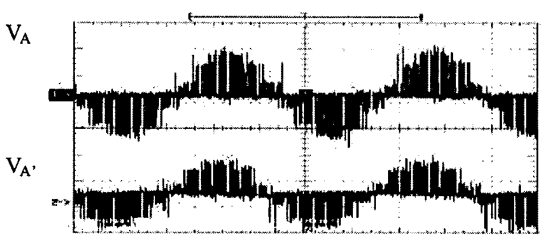


Fig.2l – Phase voltage V_A and $V_{A'}$ in phase – A and phase – A' respectively. .(with 11th and 13th suppression) Modulation index = 0.25 , **fc/f = 48** , Y-100V/div

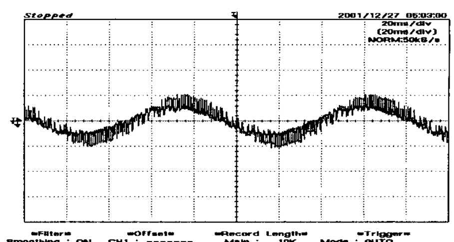


Fig.2m – Phase current I_A at no load–.(with 11th and 13th suppression) Modulation index = 0.25 , **fc/f = 48** Y-axis-1amp/div, X-axis 5ms/div

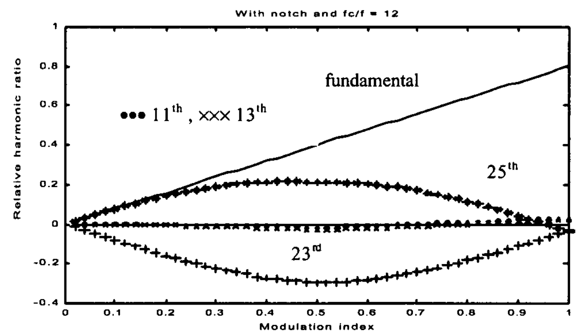


Fig.3a. Relative harmonic ratio verses modulation index. **fc/f = 12**

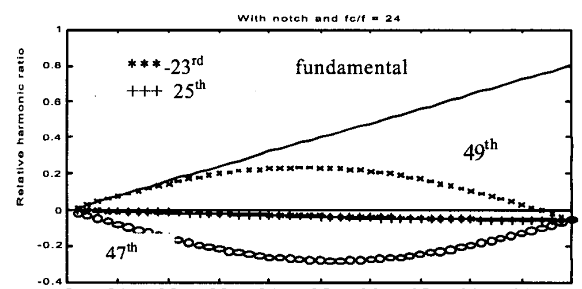


Fig.3b- Relative harmonic ratio versus modulation index- **fc/f = 24**

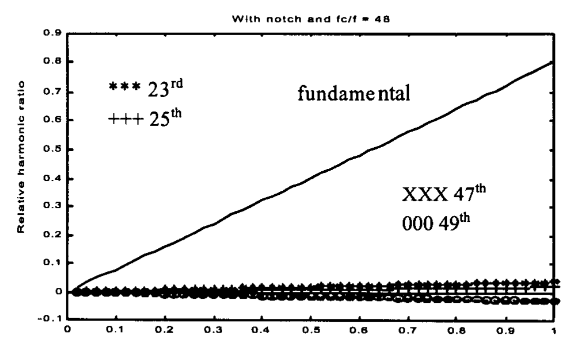


Fig.3c- Relative harmonic ratio versus modulation index- **fc/f = 48**