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A New Corrected Virtual Voltage Vector Based Space–Vector PWM Method for Nine Switch Inverters

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***Abstract* – This paper presents a Nine switch inverter (NSI) which can be used to run two loads static /dynamic or mixed loads independently. It finds application in axle mounted motors in electric traction, washing and drying motors in washing machines. This paper proposes a new Space Vector Modulation (SVM) technique. With this new SVM, two loads (static/dynamic) can be run independently. In this method, logical XOR operation is avoided. Thus circuitry requirement is considerably reduced. Hexagon drawn for three level multilevel inverter can be considered to be enclosing six hexagons along with a hexagon at the centre and each of these hexagon can be considered to be a space vector hexagon drawn for two level three phase inverter [13]. In the proposed method, first we will convert nine switch voltage vectors to its equivalent voltage vectors for six switch inverter (SSI). Then this six switch voltage vectors are again transformed back to their equivalent nine switch voltage vectors. Thus we are shifting from NSI domain to SSI domain and again going back to NSI domain. This concept was totally analyzed and is supported by sound mathematical analysis [19] . The proposed SVM method is verified by Matlab-simulation. The results have shown that output phase currents have THD less than 3% and the inverter has good harmonic performance. The inverter can be operated in CF and DF mode, total behavior of the inverter is studied for various conditions. Limitations are also presented. It is proved that with new SVM approach, both the inverters can be safely operated with modulation index sum 1.15.**

***Keywords* – Nine switch inverter, space-vector modulation, modulation index, common frequency, different frequency.**

I. INTRODUCTION

Modern industry such as processing and manufacturing industries invariably use multiple electric drives. These electric drives should be precisely and efficiently controlled without disturbing the industrial output. Power electronics has played a key role in development of modern industry. Power electronic circuits using fast acting semiconductor switches along with advanced modulation techniques have made it possible to meet the needs of modern industry. Industrial revolution started with single motor speed control using single inverter. Circuit optimization concept has resulted in development of Nine switch inverter [4], Five Leg Inverter [3] and B4 Inverter [1]. Nine switch inverter (NSI) has three legs and each leg carries three semi-conductor switches. Thus NSI consists of two 3-phase inverters such that middle switches become common to both the inverters.

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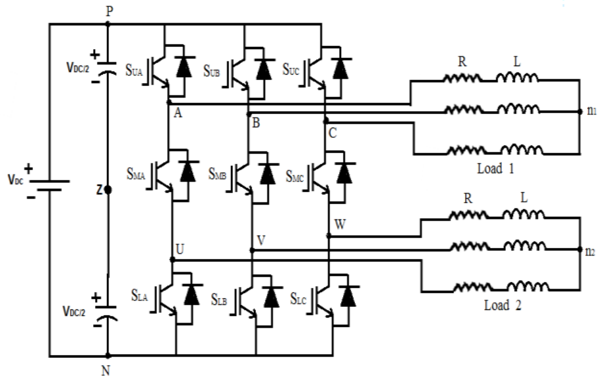


Fig. 1. Nine-switch inverter configuration

To avoid the dc supply short circuit, only two switches of a leg should be on. Also all the three switches of a leg should not be at once opened. NSI can provide output to drive the two loads independently. Though NSI can run both the loads independently but there are some limitations with regards to amplitude, phase and frequency of inverter outputs and also oversized dc link capacitor. The NSI finds applications where two motors should be independently controlled. This paper proposes a new SVM. In this method, logical XOR operation is removed . Hexagon drawn for three level multilevel inverter can be considered to be enclosing six hexagons and each of these hexagon can be considered to be a hexagon drawn for two level three phase inverter [17]. In the proposed method, first we will convert nine switch voltage vectors to its equivalent voltage vectors for six switch inverter. Then this six switch voltage vectors are again transformed back to their equivalent nine switch voltage vectors. This concept was totally analyzed and is supported by sound mathematical analysis [24] . The proposed SVM method is verified by Matlab-simulation. The results have shown that output phase currents have THD less than 3% and the inverter has good harmonic performance. The inverter can be operated in CF and DF mode with modulation index sum for both the inverters can be taken up to 1.15.

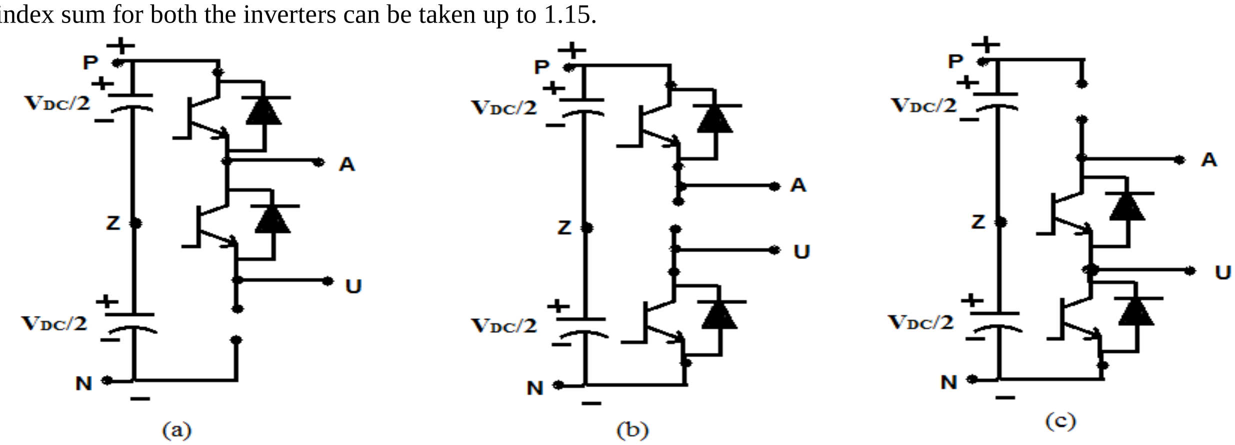


Fig. 2. Possible operation of each leg (for leg A) of Nine switch inverter.
(a) State [1], (b) State [0], and (c) State [-1].

TABLE I: THREE POSSIBLE SWITCHING STATES PER LEG (FOR PHASE X= A, B OR C)

State	Switching on off mode			v_{XN}	v_{UN}	v_{XZ}	v_{UZ}
	S_{UX}	S_{MX}	S_{LX}				
[1]	ON	OFF	ON	V_{DC}	0	$\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$

[0]	**OFF**	**ON**	**ON**	**0**	**0**	$-\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$
[-1]	**ON**	**ON**	**OFF**	V_{DC}	V_{DC}	$\frac{V_{DC}}{2}$	$\frac{V_{DC}}{2}$

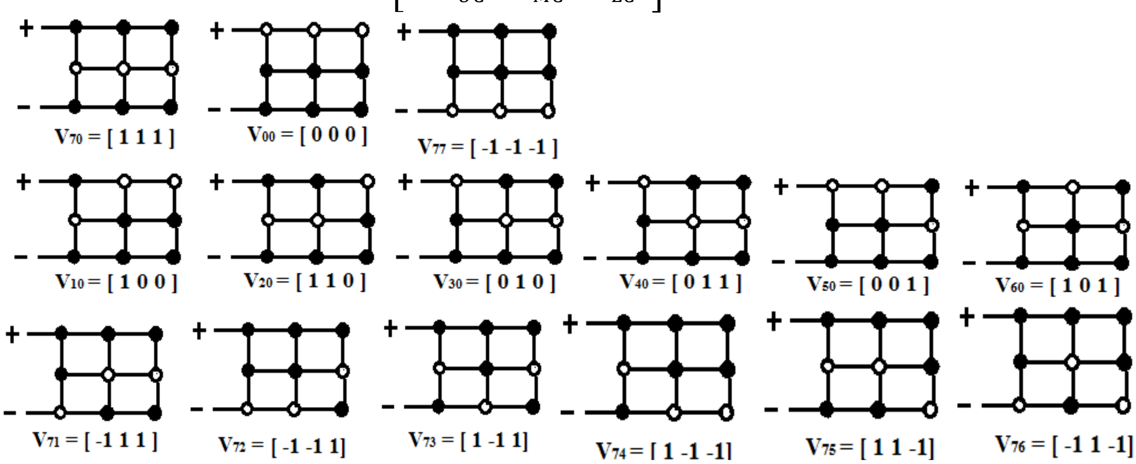
The paper has been arranged in five sections. Section – I deals with the introduction to Nine switch inverter. It's schematic circuit is presented along with the research carried out to till date and possible switching states per leg is discussed. In Section - II, all the possible 27 switching modes of NSI and corresponding voltage vector for all the modes are presented. Section – III explores the reference vector theory supported with sound mathematical analysis. In this section all the NSI voltage vectors are converted into SSI voltage vectors and again they are transformed back to NSI voltage vectors. Section – IV deals with algorithm developed to materialize the objectives quoted in section – III. The code supporting the section – III has been developed in Matlab. In Section – V, results are thoroughly discussed and limitations are explained.

II - SWITCHING MODES OF NINE SWITCH INVERTER

Three phase voltage source inverters (VSI) can be conveniently be used for precise control of variable frequency drives by proper modulation technique. The limitation with this inverter is only single drive can be controlled. Controlling multiple drives is not possible with this inverter. If multiple drives are connected, they cannot be run independently. Continuous efforts in circuit optimization has resulted in the development of NSI [4]. NSI can be considered to be embedded with two 3- phase inverters in single unit. It consists of three legs, each leg carrying three switches. The middle switches are the common switches to upper and lower inverter respectively. To avoid the short circuit of dc input source, all the three switches of a leg should never be turned on. Also all the three switches of a leg should never be opened. NSI said to be working well provided both the loads are independently controlled. Though many advanced modulation techniques along with reduced switching are available for NSI, but tradeoff has been done with regards to amplitude, frequency, phase shift limitations, and drives cannot be totally run independently. Also the device switching losses cannot be totally minimized.

The algebraic expression to be satisfied for NSI is $S_{UX} + S_{MX} + S_{LX} = 2$; here 'X ' can be A or B or C respectively. In matrix form,

$$\begin{bmatrix} S_{UA} & S_{MA} & S_{LA} \\ S_{UB} & S_{MB} & S_{LB} \\ S_{UC} & S_{MC} & S_{LC} \end{bmatrix} = [2]$$



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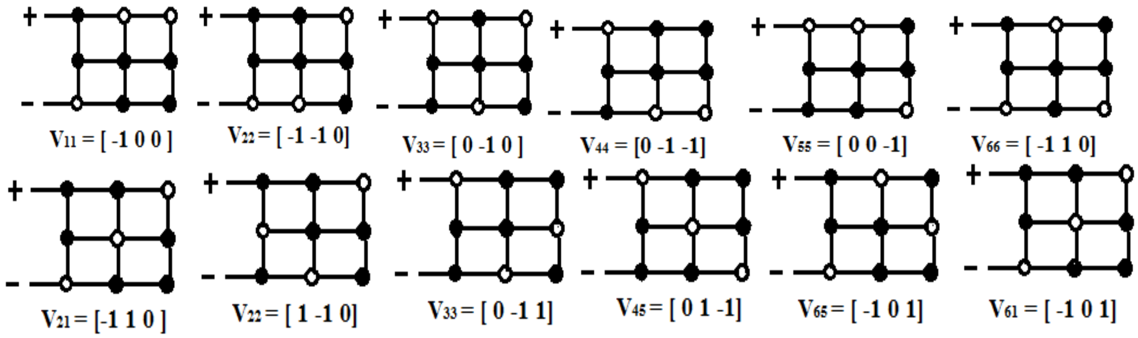

Fig. 3. 27 switching states of Nine Switch Inverter

There are 27 switching states of Nine switch inverter and are depicted in the Fig. 3. V_{70}, V_{00}, and V_{77} are null vectors. V_{10}, V_{20}, V_{30}, V_{40}, V_{50}, V_{60} are live–null vectors. V_{71}, V_{72}, V_{73}, V_{74}, V_{75}, and V_{76} are null-live vectors. V_{11}, V_{22}, V_{33}, V_{44}, V_{55}, and V_{66} are similar live-live vectors. V_{21}, V_{23}, V_{43}, V_{45}, V_{65}, and V_{61} are different live-live vectors.

Table – II describes switching modes and corresponding magnitude of voltage vector of nine switch inverter.

TABLE II: SWITCHING MODES AND CORRESPONDING VOLTAGE VECTOR OF NINE SWITCH INVERTER

Voltage vectors	Phase voltages v_{AN} , v_{BN}, v_{CN}	Pole voltages v_{AZ},v_{BZ},v_{CZ}	Line-to-line voltages v_{AB}, v_{BC} ,v_{CA}
V_{70}, V_{71}, V_{72}, V_{73}, V_{74}, V_{75}, V_{76}, V_{77},	V_{DC}, V_{DC}, V_{DC},	$\frac{V_{DC}}{2}$, $\frac{V_{DC}}{2}$, $\frac{V_{DC}}{2}$	0 , 0 , 0
V_{20},V_{21},V_{22}, V_{23}	V_{DC}, V_{DC}, 0	$\frac{V_{DC}}{2}$, $\frac{V_{DC}}{2}$, - $\frac{V_{DC}}{2}$	0, V_{DC} , -V_{DC}
V_{60} ,V_{61},V_{65},V_{66}	V_{DC}, 0 , V_{DC},	$\frac{V_{DC}}{2}$, - $\frac{V_{DC}}{2}$, $\frac{V_{DC}}{2}$	V_{DC} , -V_{DC}, 0
V_{40},V_{43},V_{44},V_{45}	0, V_{DC}, V_{DC},	-$\frac{V_{DC}}{2}$, $\frac{V_{DC}}{2}$, $\frac{V_{DC}}{2}$	-V_{DC} , 0, V_{DC}
V_{10}, V_{11}	V_{DC}, 0, 0	$\frac{V_{DC}}{2}$, - $\frac{V_{DC}}{2}$, - $\frac{V_{DC}}{2}$	V_{DC} ,0, -V_{DC}
V_{30}, V_{33}	0, V_{DC}, 0	- $\frac{V_{DC}}{2}$, $\frac{V_{DC}}{2}$, - $\frac{V_{DC}}{2}$	-V_{DC} , V_{DC}, 0
V_{50},V_{55}	0, 0, V_{DC},	- $\frac{V_{DC}}{2}$,- $\frac{V_{DC}}{2}$, $\frac{V_{DC}}{2}$	0, -V_{DC} , V_{DC}
V_{00}	0, 0, 0	- $\frac{V_{DC}}{2}$,- $\frac{V_{DC}}{2}$, - $\frac{V_{DC}}{2}$	0 , 0 , 0

III - REFERENCE VECTOR THEORY - A MATHEMATICAL APPROACH

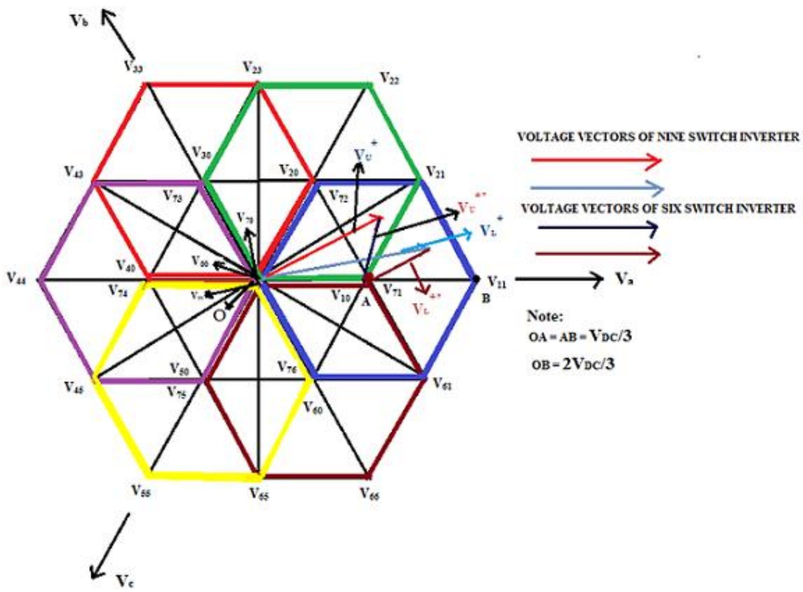

Fig. 4. NSI space-vector diagram.

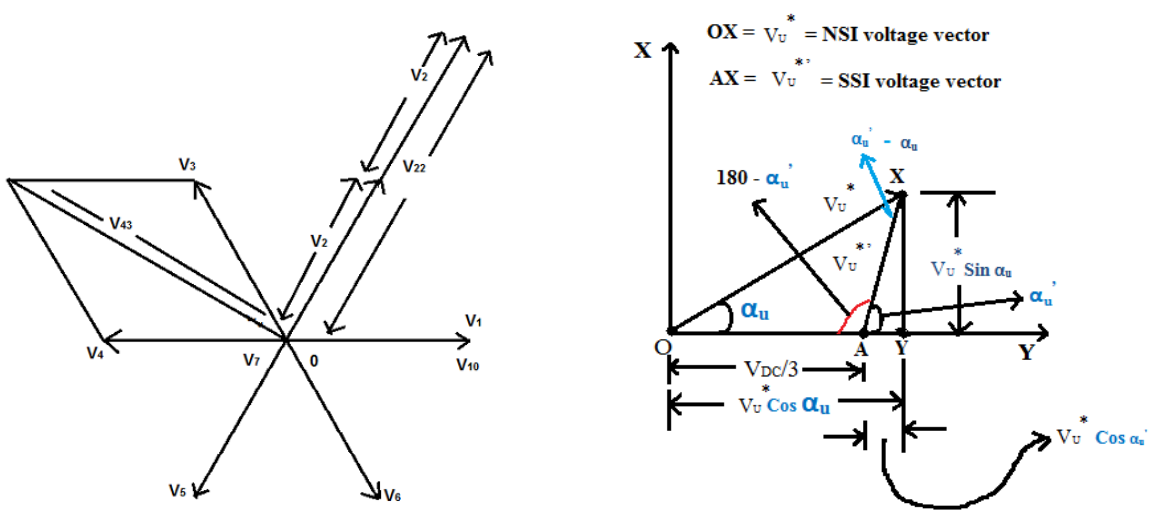

Fig. 5. Voltage vectors of NSI, (a) the vectors synthesis method of NSI with the vectors of SSI, (b) NSI voltage vector triangle.

TABLE III: SWITCHING VECTORS OF NINE SWITCH INVERTER ALONG WITH RESOLUTION OF VOLTAGES VECTORS IN SIX SWITCH CONVERTER PLANE

NS I Vector	Leg A	Leg B	Leg C	Type	Equivalent SSI vector	
					Upper	Lower
V_{70}	1	1	1	Null-null vectors	V_7	V_0
V_{00}	0	0	0		V_0	V_0

V_{77}	-1	-1	-1		V_7	V_7
V_{10}	1	0	0	Active-null vectors	V_1	V_0
V_{20}	1	1	0		V_2	V_0
V_{30}	0	1	0		V_3	V_0
V_{40}	0	1	1		V_4	V_0
V_{50}	0	0	1		V_5	V_0
V_{60}	1	0	1		V_6	V_0
V_{71}	-1	1	1	Null-active vectors	V_7	V_1
V_{72}	-1	-1	1		V_7	V_2
V_{73}	1	-1	1		V_7	V_3
V_{74}	1	-1	-1		V_7	V_4
V_{75}	1	1	-1		V_7	V_5
V_{76}	-1	1	-1		V_7	V_6
V_{11}	-1	0	0	Similar active-active vectors	V_1	V_1
V_{22}	-1	-1	0		V_2	V_2
V_{33}	0	-1	0		V_3	V_3
V_{44}	0	-1	-1		V_4	V_4
V_{55}	0	0	-1		V_5	V_5
V_{66}	-1	0	-1		V_6	V_6
V_{21}	-1	1	0	Different active-active vectors	V_2	V_1
V_{23}	1	-1	0		V_2	V_3
V_{43}	0	-1	1		V_4	V_3
V_{45}	0	1	-1		V_4	V_5
V_{65}	1	0	-1		V_6	V_5
V_{61}	-1	0	1		V_6	V_1

All the '27' switching states of NSI forms the corners of outer and inner hexagon respectively. $\mathbf{V_{70}}$ represent the real voltage vector of NSI. This voltage vector can be synthesized into two vectors which are namely **V_7 and V_0** respectively. **V_7 and V_0** are the virtual null voltage vectors of SSI respectievely. $\mathbf{V_{71}}$ represesent the real voltage vector of NSI, can be synthesized into $\mathbf{V_7}$ $\mathbf{V_1}$. It is to be noted that $\mathbf{V_1}$, $\mathbf{V_2}$, $\mathbf{V_3}$, $\mathbf{V_4}$, $\mathbf{V_5}$, $\mathbf{V_6}$, $\mathbf{V_0}$, and $\mathbf{V_7}$ are the virtual active voltage vectors of six-hexagons which are part of NSI space vector diagram. Thus NSI space vector diagram contains two-level six hexagons. Hence all the mathematical equations of NSI can be expressed in terms of two-level hexagon virtual vectors. Fig. 5 (b) shows voltage vector triangle of NSI. Here **OA** represents the centre voltage vector. $\mathbf{VU^*}$ represents reference active voltage of NSI makes an angle $\boldsymbol{\alpha_u}$ with the horizontal axis. The component of VU^* on the horizontal axis is VU^* **Cos** $\boldsymbol{\alpha_u}$. From the triangle,

$$\mathbf{OX} = V_U^* \ \mathbf{Cos}\ \boldsymbol{\alpha_u} \ \textbf{and}$$

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$$AY = (V_U^{*}\ \mathrm{Cos}\ \alpha_u - V_{DC}/3)^{1/2}$$

$$XY = V_U^{*}\ \mathrm{Sin}\ \alpha_u$$

$$\therefore AX = V_U^{*'} = ((V_U^{*}\ \mathrm{Cos}\ \alpha_u - V_{DC}/3)^{1/2} - V_U^{*}\ \mathrm{Sin}\ \alpha_u)^{1/2}$$

Similarly, $V_L^{*'} = ((V_L^{*}\ \mathrm{Cos}\ \alpha_l - V_{DC}/3)^{1/2} - V_L^{*}\ \mathrm{Sin}\ \alpha_l)^{1/2}$

From sine theorem,

$$(V_{DC}/3)/(\mathrm{Sin}\ (\pi - (\alpha_u - \alpha_u'))) = (V_U^{*})/\ \mathrm{Sin}\ (\pi - \alpha_u') = V_U^{*'}\ /\ \mathrm{Sin}\ \alpha_u$$

$$\therefore \mathrm{Sin}^2\ \alpha_u' = ((V_U^{*})^2\ \mathrm{Sin}^2\ \alpha_u)\ /\ [((V_U^{*})^2\ \mathrm{Sin}^2\ \alpha_u) + (V_U^{*}\ \mathrm{Sin}\ \alpha_u - V_{DC}/3)^{1/2}]$$

Also $\mathrm{Sin}^2\ \alpha_l' = ((V_L^{*})^2\ \mathrm{Sin}^2\ \alpha_l)\ /\ [((V_L^{*})^2\ \mathrm{Sin}^2\ \alpha_l) + (V_L^{*}\ \mathrm{Sin}\ \alpha_l - V_{DC}/3)^{1/2}]$

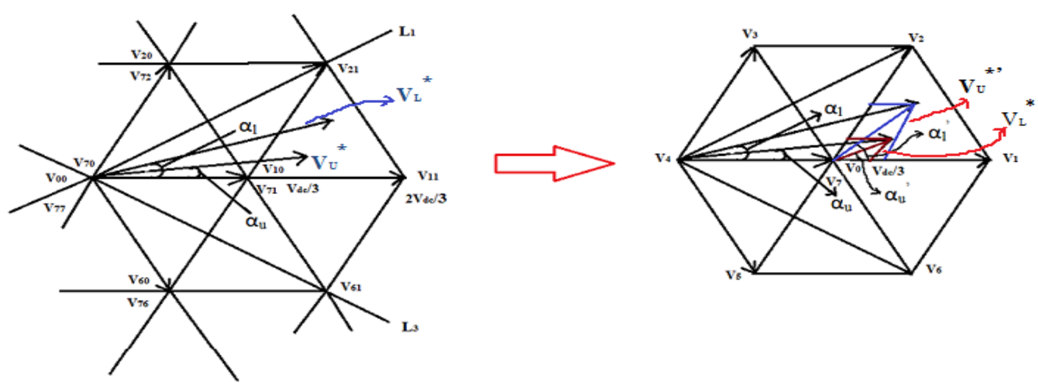

Fig. 6. (a) NSI vectors VU^{*} and $\mathbf{VL}^{*}$are in same space enclosed by L_1 & L_3 where as SSI vectors $V_U^{*'}$ **and** $V_L^{*'}$ are also in the same sector.

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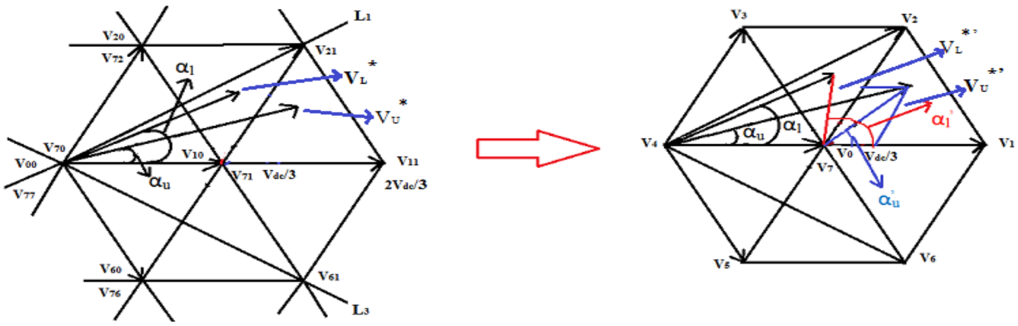

Fig. 6. (b) NSI vectors VU* and **VL***are in same space enclosed by L_1 & L_3 where as SSI vectors **$V_U^{*'}$ and** $V_L^{*'}$ are also in the adjacent sector.

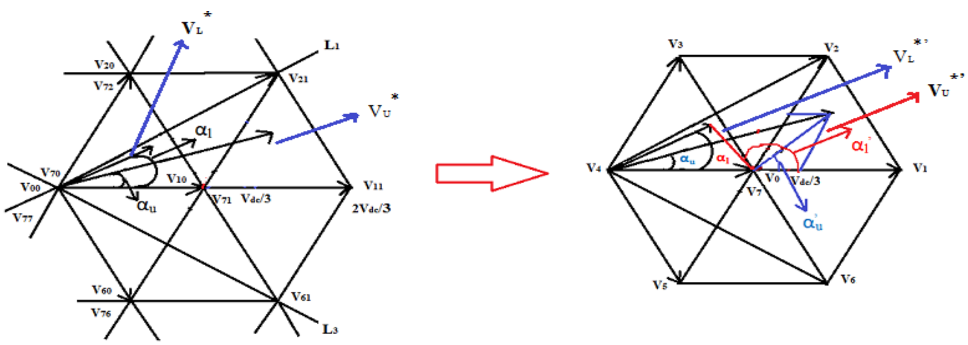

Fig. 6. (c) NSI vectors VU* and **VL***are in same space enclosed by L_1 & L_3 where as SSI vectors **$V_U^{*'}$ and** $V_L^{*'}$ are also in the far off sector.

IV - FOUR STEPS IN ALGORITHM FORM.

1. Identification and Location of NSI reference vectors for upper and lower inverter in the NSI space vector diagram.
2. Subtract V_{DC} /3 or V_{DC}/6 (centre vector) from NSI reference vector based on their location. This step will transform from NSI space vector domain to SSI space vector domain.
3. NSI voltage vector for upper inverter is of the form $\mathbf{V}^*_{XY(U)}$, the transformed NSI voltage vector to SSI space vector plane will be $\mathbf{V}^{*'}_{XY(U)}$ respectively. This will have two components $\mathbf{V}^{*'}_{X(U)}$ **and** $\mathbf{V}^{*'}_{Y(U)}$ respectively. Correspondingly the dwell timings are determined.
4. Based on dwell timings conditions, switching must be followed. There by SSI voltage vectors are transformed back to NSI space vector domain.

V – MATLAB SIMULATION CIRCUIT, RESULTS AND EXPLANATION

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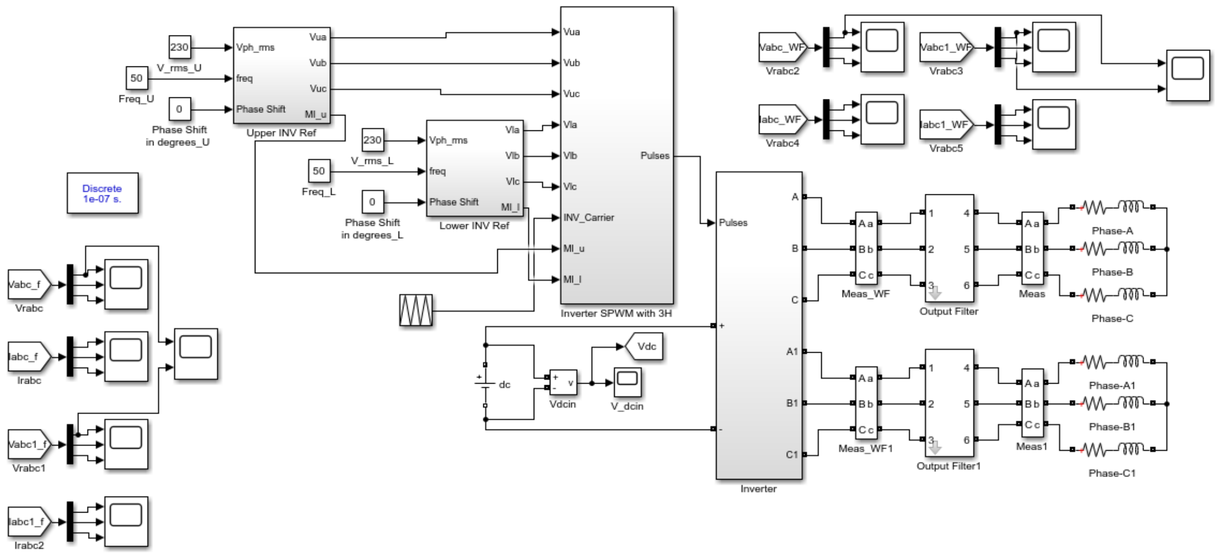


Fig. 7. Simulation diagram of Nine switch Inverter.

SYSTEM PARAMETERS: R = 60 Ω, L = 10 mH, V_{DC} = 700 V, V_{ref-1} = 230 V, V_{ref-2} = 230 V, Phase angle difference = 0˚, f_1 and f_2 = 50 Hz, Modulation Index = 0.93 (for upper and lower inverter respectively) and $T_s = 3.3 * 10^{-5}$ Seconds.

Output waveforms for RL-load :

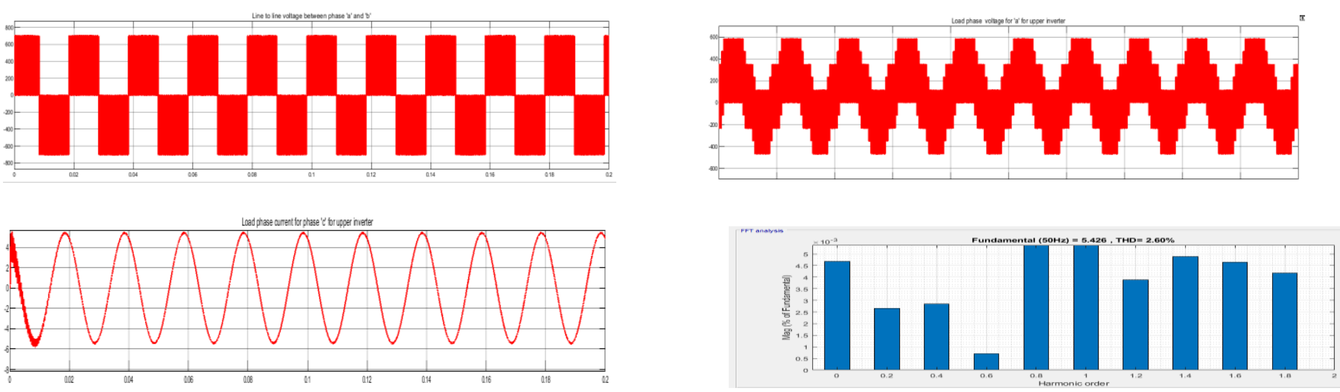
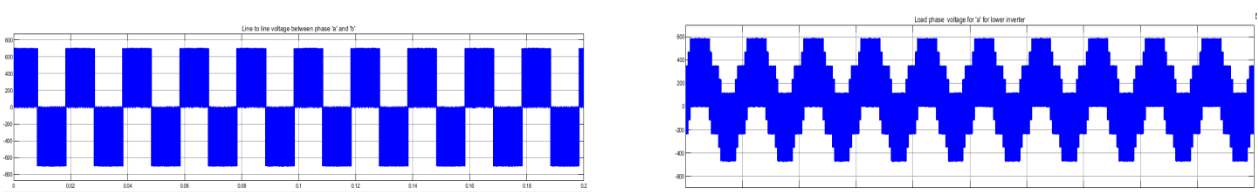


Fig. 8. (a) Line to line load voltage V_{ab} for upper inverter. (b) Load phase voltage for 'a' phase. (c) Load current of phase 'c'. (d) Harmonic spectrum for 'RL' load – Upper inverter



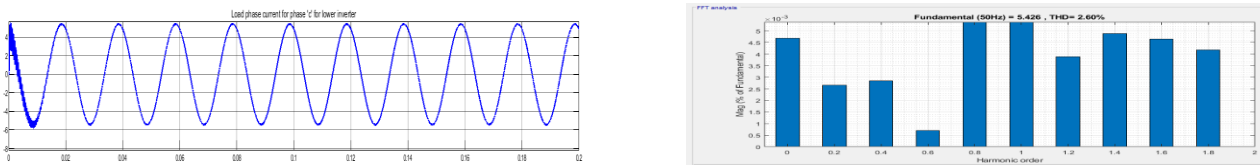
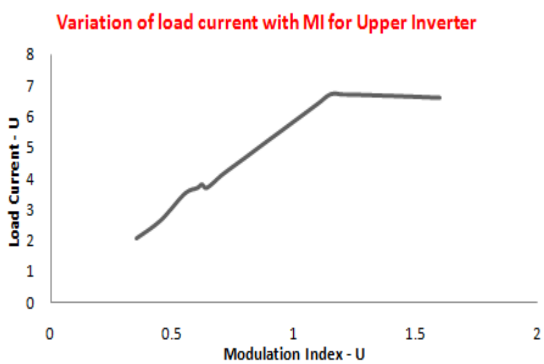
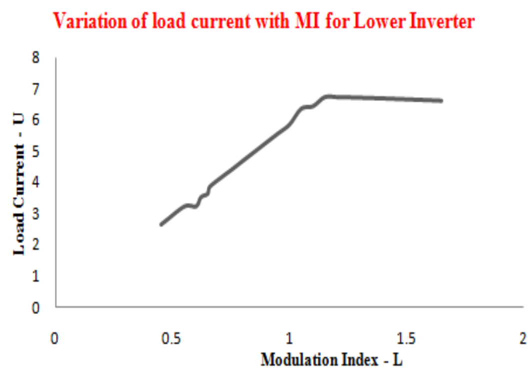


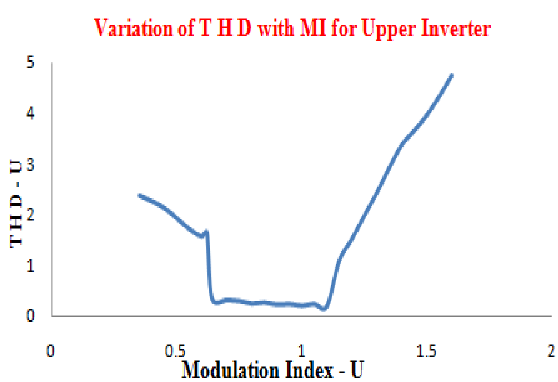
Fig.9. (a) Line to line load voltage V_{ab} for upper inverter. (b) Load phase voltage for ‘a’ phase. (c) Load current of phase ‘c’. (d) Harmonic spectrum for ‘RL’ load – Lower inverter

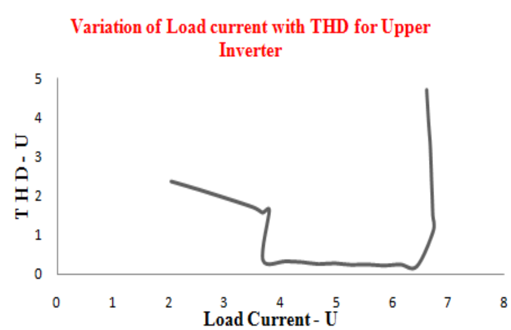
The forthcoming focus on the operation of NSI along with its limitations. Upper and lower inverter behavior is studied at equal frequency, different frequency and at different phase angles respectively.

AT COMMON FREQUENCY: Both inverters working at equal frequency









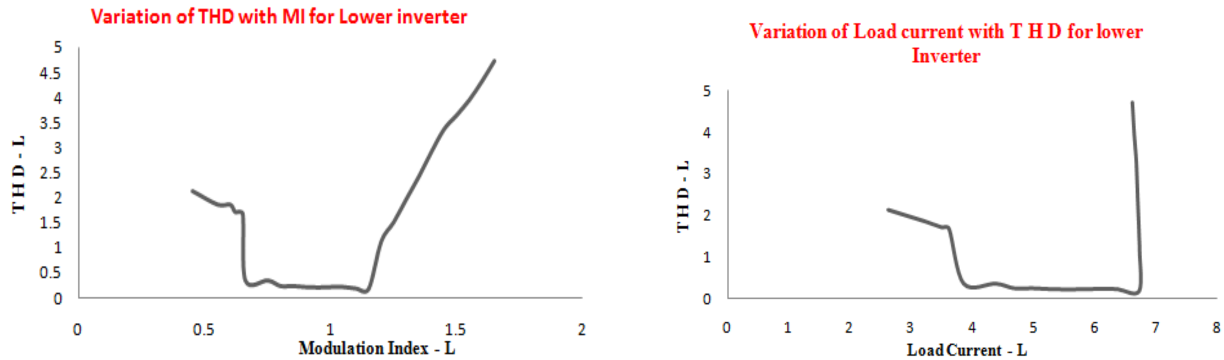


Fig.10. (a) Variation of load current with MI for upper inverter. (b) Variation of THD with MI for upper inverter. (c) Variation of load current with THD for upper inverter. (d) Variation of load current with MI for lower inverter. (e) Variation of THD with MI for lower inverter. (f) Variation of load current with THD for lower inverter.

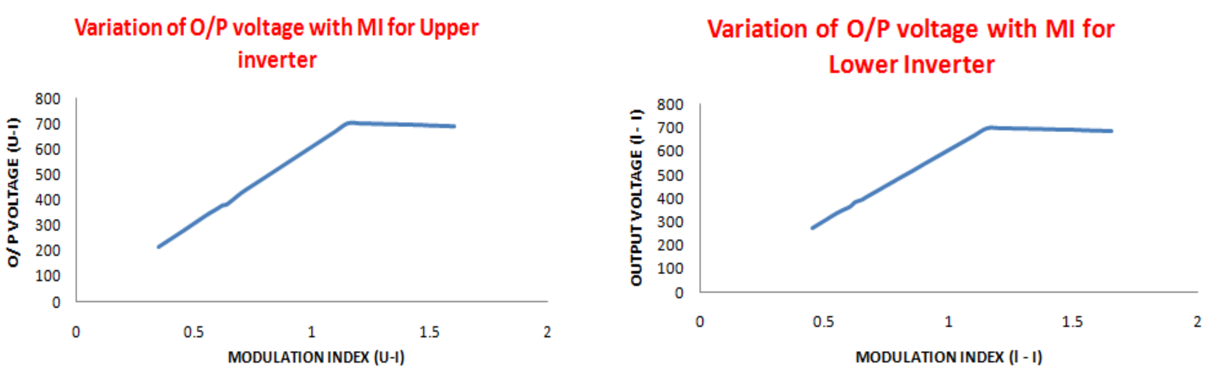


Fig. 11. Variation of output voltage with modulation index for upper and lower inverter at dc bus utilization

The characteristics obtained above are when output frequency is stationed at one value, at 50 Hz and modulation index (MI) is varied from 0.35 to 1.75 for upper upper and lower inverter respectively. From figure (a) and (d) as MI increases load current increases uniformly and reaches a constant value and maintained constant. From figure (b) and (e) as MI increases THD decreases linearly and reaches a constant value and maintained constant upto a certain value and beyond MI equals 1.15 THD increases. Thus this places a limit on the operation if NSI in common frequency (CF) mode. Figure (c) and (f) shows the variation of variation THD versus the load current for both the inverters respectively. There is safe a limit for all values of MI below 1.3 and beyond this static and dynamic losses are tremendously increased. Even too low values of MI burdens inverter. Thus while operating the inverter, optimal values of MI should be selected.

AT DIFFERENT FREQUENCY : The characteristics obtained below are when switching frequency of upper inverter is stationed 50 Hz and output frequency of lower inverter is varied keeping the modulation index (MI) fixed for upper upper and lower inverter respectively.

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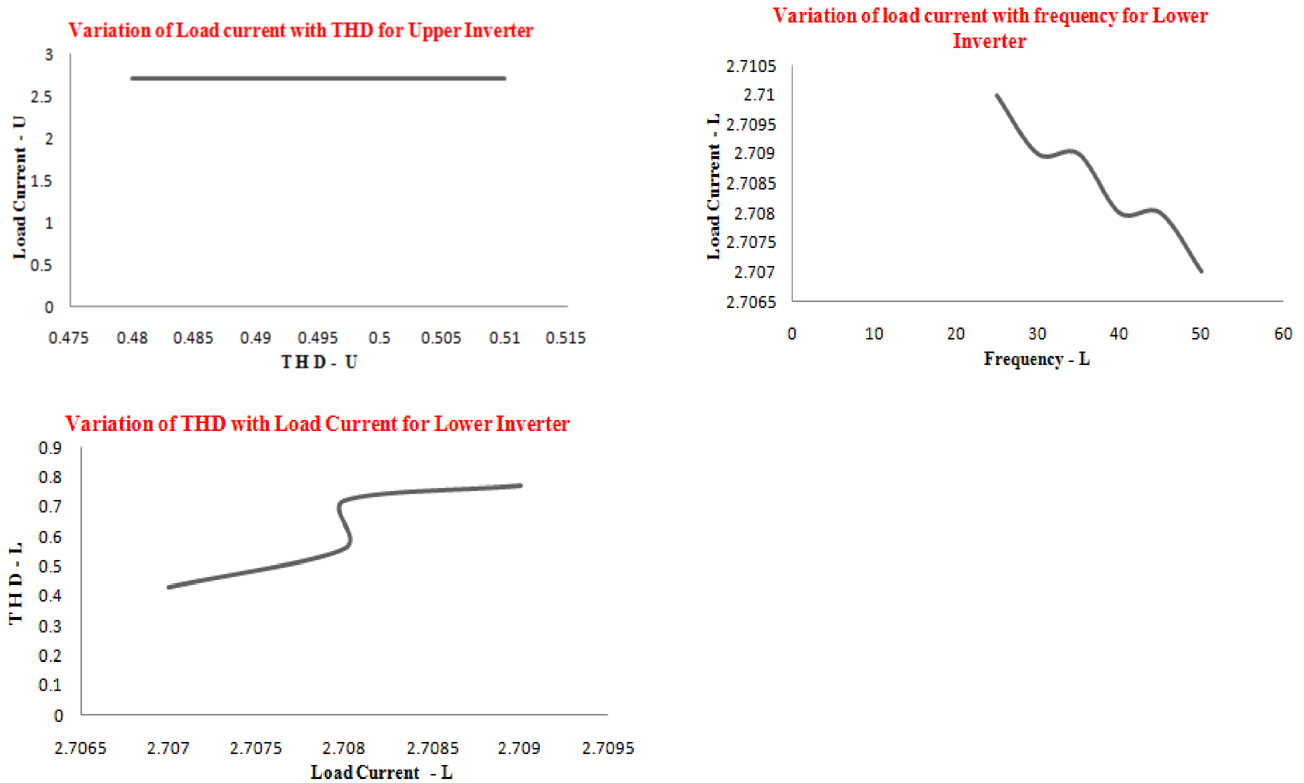

Fig.12. (a) Variation of load current with THD for upper inverter. (b) Variation of load current with frequency for upper inverter. (c) Variation of THD with load current for upper inverter.

Load current drawn by upper inverter remains constant where as load current for lower inverter decreases as output frequency of lower inverter decreases. From figure (a) and (c) THD for upper and lower inverter increases. Thus at large difference in frequency may lead to steady state and transient losses.

AT DIFFERENT PHASE ANGLES: Both inverters working at equal frequency with equal reference voltages but operating at different phase angles.

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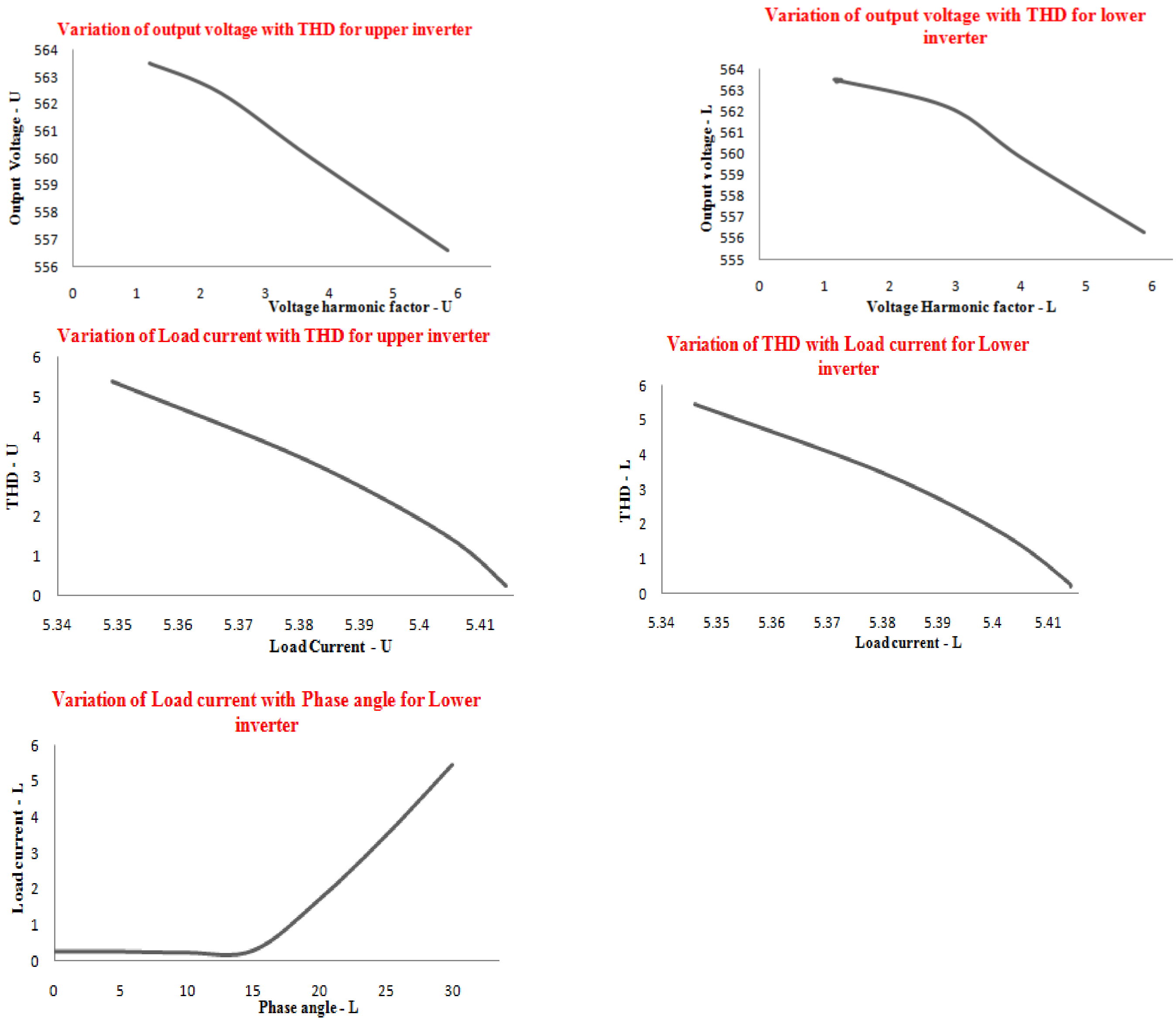

Fig.13. (a) Variation of output voltage with THD for upper inverter. (b) Variation of output voltage with THD for upper inverter. (c) Variation of load current with THD for upper inverter. (d) Variation of load current with THD for lower inverter. (e) Variation of load current with phase angle for lower inverter.

The characteristics obtained above are when phase angle of lower inverter is varied. Phase angle for upper inverter is kept fixed at 0˚. Voltage harmonics are also correspondingly increased as similar to current harmonics with the variation of phase angle. Figure (d) indicates that upto 15˚, lower inverter load current remains at lower value and maintains constant value. Thus inverter losses are also at lower value. Above 15˚ load current increases linearly with phase angle and thereby losses are increased. Thus maxiumum phase angle limit is 15˚, beyond which, THD crosses IEEE limits.

VI - CONCLUSION

This paper presents a Nine switch inverter (NSI) which can be used to run two loads static /dynamic or mixed loads independently. It finds application in axle mounted motors in electric traction, washing and drying motors in washing machines. This paper proposes a new Space Vector Modulation (SVM) technique. With this new SVM, two loads (static/dynamic) can be run independently. The proposed SVM method is verified by Matlab-simulation. The results have shown that output load currents have THD less than 3% and the inverter has good harmonic performance. The inverter can be operated in CF and DF mode with modulation index sum for both the inverters can be taken up to 1.15.

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