Resultant Theory and Jenkins-Traub Algorithm Based SHEPWM using Assimilated Software Environment for a Seven Level VSI

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Abstract–The staircase, sinusoidal like output ac voltage waveform of a multilevel inverter (MLI) can offer a higher output voltage but fails to have an easy filterable harmonic spectrum as MLIs of higher number of levels can only suppress the lower order harmonics and the total harmonic distortion (THD). Increasing the level may complicate the power circuit and control, and also increases the cost. An effective pulse width modulation (PWM) method with an inherent property of reducing the lower harmonics with the reduced level is proposed in this paper. An ingenious solution to the persisting problem of eliminating specific lower order harmonics in MLI can help in minimizing the circuit complexity. The crux of the selective harmonic elimination (SHE) method is resultant theory based estimation of switching instants for the entire working range of a single phase MLI using a developed assimilated software environment (ASE). The ASE replaces the principal transcendental equations by polynomial equation of higher order and then reduces the order using elimination theory using Mathematica® solved by the Jenkins-Traub algorithm in a Visual C++ platform. The MATLAB/Simulink based simulation results are corroborated in a fabricated prototype for elimination of the third, fifth and seventh harmonics.

Keywords–Assimilated software environment (ASE), multi-level inverter (MLI), selective harmonic elimination (SHE), resultant theory, total harmonic distortion (THD)

I. INTRODUCTION

The basic idea behind any pulse width modulation (PWM) strategy employed in voltage source inverter (VSI) is shifting the dominant harmonic from low order to higher order and hence reducing the filtering efforts [1-2]. The traditional sine-triangle PWM method and its variants perform this task at few kHz and commonly acceptable in applications where switching losses are not a concern [3]-[5]. Multilevel inverters (MLIs) are the relatively complex structures which can produce an ac voltage with a reasonably reduced total harmonic distortion (THD) and switching losses. Even though the typical MLI output voltage spectrum has suppressed lower order harmonics, the dead band and filtering requirements are inferior to conventional natural sampled PWM methods [6]-[7]. Incorporation of selective harmonic elimination (SHE) theory with the low switching operation of MLI makes the system more attractive, as it further reduces the filtering requirements. This combination is well suited for application like ac drives, flexible ac transmission systems (FACTS) etc. SHEPWM is special kind of regular sampled PWM, which can result in acceptable spectral quality with low switching frequency.

In SHEPWM, inverter switching instants are determined by solving a set of nonlinear transcendental equations, which are formulated from Fourier analysis. SHEPWM was introduced by Patel and Hoft in 1973 [8]. The principle of SHE is, that for any value of target output voltage (hence modulation index) there will be set of switching angles to equalize the Fourier coefficients associated with the required harmonics to zero. Thus SHEPWM is meant to place switching edges to eliminate required harmonic.

A modulation-based method for generating pulse waveforms with SHE has been proposed, which functions without transcendental equations [9]. The gating pulses have been obtained by comparison of a sine wave with modified triangular carrier while all existing SHE algorithms are digital (regular sampled). One alternative to the hassle free Fourier series formulation has been the orthonormal set based on Walsh functions [10]. By using the Walsh domain waveform analytic technique, the harmonic amplitudes of the inverter output voltage can be expressed as functions of switching angles. Thus, the switching angles are optimized by solving linear algebraic equations instead of solving nonlinear transcendental equations. The resulting equations are more tractable due to the similarities between the rectangular Walsh function and the desired waveform. Newton-Raphson method although being an iterative method does not guarantee all the possible solutions of determining the required switching angles [11]. A method has been developed to work with the SHE technique for sinusoidal voltage generation applied to control static VAR compensators [12]. Homotopy method allows higher degree of freedom by solving the harmonic pulses graphically. The fundamental wave component is considered as the Homotopy parameter [13]. Recently, evolutionary search algorithms like genetic algorithm (GA), particle swarm optimization (PSO), bacterial foraging (BF) algorithm with their good convergence rate have pitched in and played there greater role in determining their optimum switching angles needed for SHE [14-16].

The main challenge associated with existing SHE techniques is either obtaining the analytical solutions of nonlinear transcendental equations (contain trigonometric terms which naturally exhibit multiple solutions) or the solution accelerating starting values (the close proximity of the starting values to the exact solutions ensures convergence). This paper provides systematic and sequential approach to overcome such difficulty of solving the equations. The principal transcendental equations are

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mapped into higher order polynomial equation. Later these higher order polynomials are reduced using elimination theory by computing the resultant of the polynomial. Software package Mathematica®6 is employed to explore the theory of resultants. The switching angles are predetermined using the software tool developed in Visual C++ based on Jenkins-Traub algorithm. Experimental results support the theoretical considerations and simulated results reported in the paper.

II. Proposed SHE Algorithm

The Proposed procedure is an offline method of determining the switching angles for the proposed seven level MLI. The entire algorithm is divided into two stages. The initial stage of mathematical formulations is based on Fourier analysis and its associated trigonometric summations and substitutions. The second stage involves the resultant theory and the Jenkin-Traub algorithm which deals with higher order polynomial and calculations of the switching angles required to eliminate or cancel the lower order odd harmonics. The resultant theory method of formulating the equations involves the usage of Mathematica®.The steps are indicated in Fig.1.

A.MLI and SHE

The cascaded MLI consists of several single-phase H-bridge inverters with separate DC sources as illustrated in Fig.2 [17]. This structure can avoid extra clamping diodes or voltage clamping capacitors [18]. An example of the output voltage waveform for a seven-level cascaded inverter is diagrammed in Fig.3. For a cascaded MLI, the number of output phase voltage levels is defined by $m=2S+1$, where 'S' is the number of DC sources and 'm' is the number of inverter levels.

The output voltage, V_{AB} obtained is a summation individual H-bridge outputs ($V_1+V_2+V_3$). The real valued Fourier series of the (stepped) output voltage waveform of the multilevel inverter is written as

$$V_0(\omega t) = a_0 + \sum_{n=1}^{\infty} a_n \sin n\omega t + \sum_{n=1}^{\infty} b_n \cos n\omega t \quad (1)$$

The DC component, $a_0 = 0$. Cosine component and even order sine component do not exist, while the fundamental component wave and the odd order sine harmonic components are as follows : (b_n=0)

$$a_n = \frac{4V_{dc}}{n\pi}[\cos n\alpha_1 + \cos n\alpha_2 + \cos n\alpha_3] \quad (2)$$

Substituting the values of a_0, a_n and b_n, the instantaneous output voltage equation can be obtained.

$$V_0(\omega t) = \frac{4V_{dc}}{\pi}\sum_{n=1,3,5}^{\infty}\frac{1}{n}[\cos(n\alpha_1) + \cos(n\alpha_2) + \cos(n\alpha_3)]\sin n\omega t \quad (3)$$

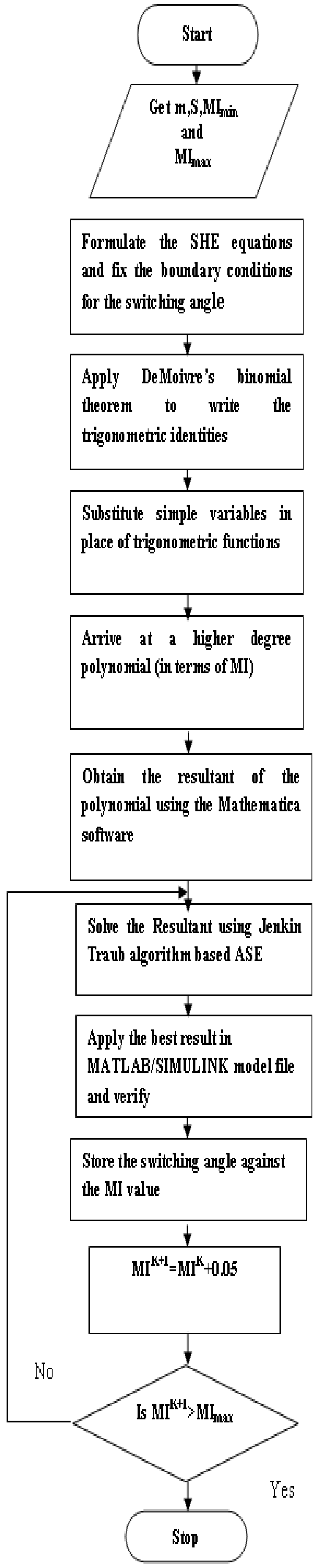

Fig. 1: Flow chart of proposed SHE algorithm

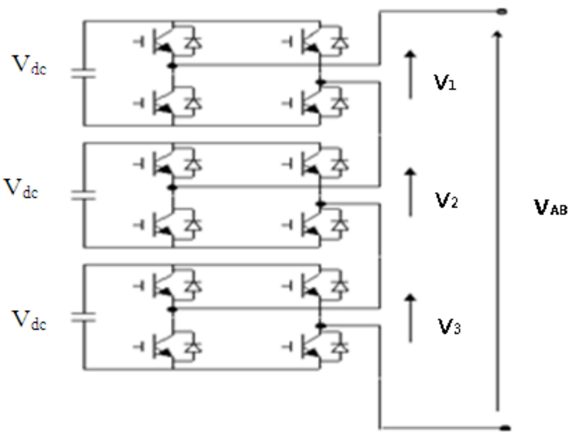

Fig. 2: Structure of a seven level cascaded H-bridge Inverter

The equation obtained will lead to two fold solutions ; (i) to obtain the required fundamental voltage by calculating the appropriate switching angles so that (*S-1*) harmonics can be removed from the voltage waveform and (ii) to minimize the THD [19-21]. Here, '*n*' is the order of harmonics and it exists only for odd. For a given desired fundamental peak voltage V_1, it is required to determine the switching angles such that $0 \le \alpha_1 < \alpha_2 < \ldots\ \alpha_s \le \pi/2$.

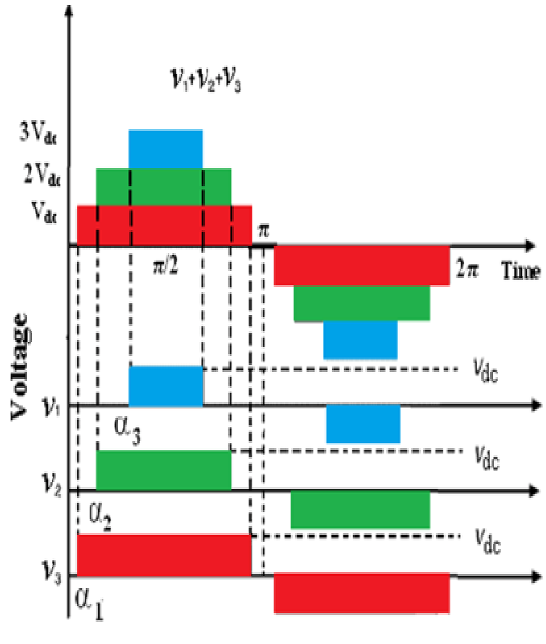

Fig.3: Output waveform of a seven level cascaded H-bridge inverter

The single-phase seven-level MLI considered has three DC sources and the default eliminations are for third, fifth and seventh harmonics as they tend to dominate the spectrum. The switching angles are chosen in such a way that they eliminate the lower frequency harmonic and also that the THD is minimized. Instants α_1, α_2 and α_3 in Fig.3 represent a sample indication of optimal angles using the proposed method with the condition $0 \le \alpha_1 < \alpha_2 < \alpha_3 \le \frac{\pi}{2}$.

The switching instants and output levels of the considered MLI is presented in Table 1. Moreover, the relation between the fundamental voltage and the maximum obtainable voltage is given by modulation index, $MI = V_1 * \pi / (s * 4 * V_{dc})$.

Table 1: Switching states of cascaded seven level inverter

switching angles	V_{a1}	V_{a2}	V_{a3}	V_{an}
$\alpha \le \alpha_1$	0	0	0	0
$\alpha_1 < \alpha < \alpha_2$	V_{dc}	0	0	V_{dc}
$\alpha_2 < \alpha < \alpha_3$	V_{dc}	V_{dc}	0	$2V_{dc}$
$\alpha_3 < \alpha < \pi/2$	V_{dc}	V_{dc}	V_{dc}	$3V_{dc}$

$$\frac{4V_{dc}}{\pi}\left(\cos\alpha_1 + \cos\alpha_2 + \cos\alpha_3\right) = V_1$$

$$\left(\cos 3\alpha_1 + \cos 3\alpha_2 + \cos 3\alpha_3\right) = 0$$

$$\left(\cos 5\alpha_1 + \cos 5\alpha_2 + \cos 5\alpha_3\right) = 0$$

$$\left(\cos 7\alpha_1 + \cos 7\alpha_2 + \cos 7\alpha_3\right) = 0 \qquad (4)$$

The set of equations grouped in (4) are redefined using trigonometric identities i.e by binomial and DeMoivre's formulae [23].

$$\cos(3\alpha) = -3\cos(\alpha) + 4\cos^3(\alpha)$$
$$\cos(5\alpha) = 5\cos(\alpha) - 20\cos^3(\alpha) + 16\cos^5(\alpha)$$
$$\cos(7\alpha) = -7\cos(\alpha) + 56\cos^3(\alpha) - 112\cos^5(\alpha) + 64\cos^7(\alpha) \qquad (5)$$

The total number of harmonics to be eliminated is taken as two, which are either 3rd and 5th or 5th and 7th or 3rd and 7th. To attain such an objective a specific set of equations is to be formulated. The equations obtained by using the trigonometric identities are quite lengthy and contains many common terms so, for the sake of simplification. For seven level (*S*=3). Let:

$$x_1 = \cos(\alpha_1)$$
$$x_2 = \cos(\alpha_2)$$
$$x_3 = \cos(\alpha_3) \qquad (6)$$

On substitution of (6) in (4) becomes

$$\frac{4V_{dc}}{\pi}\left(x_1 + x_2 + x_3\right) = V_1 \qquad (7)$$

$$\left(x_1 + x_2 + x_3\right) = \frac{V_1\pi}{4V_{dc}} \qquad (8)$$

$$\left(x_1 + x_2 + x_3\right) = M$$

$$\rightarrow \quad p_1(x) \qquad (9)$$

where, $M=\frac{V_1\pi}{4V_{dc}}$. The resultant polynomial equations are represented using the script of $p_1(x)$. This assumption holds good for the other equations such as $p_3(x)$, $p_5(x)$, $p_7(x)$.

For the set (5), the equation takes the form as follows

$$-3(x_1+x_2+x_3)+4(x_1^3+x_2^3+x_3^3)=0 \quad (10)$$

$$\text{(i.e)} \sum_{i=1}^{3}\left(-3x_i+4x_i^3\right)=0 \rightarrow p_3(x) \quad (11)$$

$$5(x_1+x_2+x_3)-20(x_1^3+x_2^3+x_3^3) + 16(x_1^5+x_2^5+x_3^5)=0 \quad (12)$$

$$\text{(i.e)} \sum_{i=1}^{3}\left(5x_i-20x_i^3+16x_i^5\right)=0 \rightarrow p_5(x) \quad (13)$$

$$\text{(i.e)} \sum_{i=1}^{3}\left(-7x_i+56x_i^3-112x_i^5+64x_i^7\right)=0 \rightarrow p_7(x) \quad (14)$$

(4) becomes,

$$\begin{aligned} p_1(x) &= x_1+x_2+x_2-M=0 \\ p_3(x) &= 0 \\ p_5(x) &= 0 \\ p_7(x) &= 0 \end{aligned} \quad (15)$$

Thus, there are set of four equations which are transcendental in nature. This transcendental equation requires unique method of finding solutions. There are three unknowns namely x_1, x_2 and x_3. They are higher order polynomials, which has to be solved. The value of $x=(x_1, x_2, x_3)$, so, there are four equations with three unknowns $0 \le x_3 \le x_2 \le x_1 \le 1$.

B. Mapping of Transcendental Equations into Polynomial

The numerical analysis involves solving the set of polynomial equations to predetermine the switching angles. But for nonlinear equations convergence is crucial [15]. The work done previously [19], [26-27] have shown that the transcendental equations characterizing the harmonic content can be converted into polynomial equations which are the solved using the method of resultants from elimination theory [28]. The resultant of two polynomials is well known and is implemented in many computer algebra systems [18]. It is a powerful tool for finding solutions of equations. Substituting, ($M = m$) and $x_3=m-x_1-x_2$ in (11), (13) and (14) for the sample case for elimination of 5th and 7th harmonics, results the following equation.

$$\begin{aligned} p_5(x_1,x_2) &= 5x_1-20x_1^3+16x_1^5+5x_2-20x_2^3 \\ &+16x_2^5+5(m-(x_1-x_2))-20(m-x_1-x_2)^3 \\ &+16(m-x_1-x_2)^5 \end{aligned} \quad (16)$$

$$\begin{aligned} p_7(x_1,x_2) &= -7x_1+56x_1^3-112x_1^5+64x_1^7-7x_2+56x_2^3 \\ &-112x_2^5+64x_2^7-7(m-x_1-x_2) \\ &+56(m-x_1-x_2)^3-112(m-x_1-x_2)^5 \\ &+64(m-x_1-x_2)^7 \end{aligned} \quad (17)$$

Now the two polynomials need to be solved using methods of resultant with the theory of resultants is that the two invariable polynomials will have a common root if and only if the polynomial function of the coefficient is zero. For each fixed, x_1 the pair of polynomials, $p_5(x_1,x_2)=0, p_7(x_1,x_2)=0$ has a solution x_2 if and only if the corresponding resultant matrix is singular. The determinant of the resultant matrix is a polynomial in x_1. Obtaining the specific harmonic equations may be possible by manual computation their collective solution becomes more tedious and impossible in some cases. Employing versatile computational software like Mathematica®6 would be a wiser decision. It has been conceived by Stephen Wolfram and developed by Wolfram Research of Champaign, Illinois [24].

$$\begin{aligned} p_5(x_1,x_2) &= 5m-20m^3+16m^5+60m^2x_1-80m^4x_1 \\ &-60mx_1^2+160m^3x_1^2-160m^2x_1^3+80mx_1^4 \\ &+60m^2x_2-80m^4x_2-120mx_1x_2+320m^3x_1x_2 \\ &+60x_1^2x_2-480m^2x_1^2x_2+320mx_1^3x_2-80x_1^4x_2 \\ &-60mx_2^2+160m^3x_2^2+60x_1x_2^2-480m^2x_1x_2^2 \\ &+480mx_1^2x_2^2-160x_1^3x_2^3-160m^2x_2^3+320mx_1x_2^3 \\ &-160x_1^2x_2^3+80mx_2^4-80x_1x_2^4 \end{aligned} \quad (18)$$

Similarly, $p_7(x_1, x_2)$ can also be computed.

$$deg_{x_2}\{(p_5(x_1,x_2))\}=4 \quad (19)$$

$$deg_{x_2}\{(p_7(x_1,x_2))\}=6 \quad (20)$$

$$p_5(m,x_2)=5m-20m^3+16m^5 \quad (21)$$

$$p_7(m,x_2)=7m+56m^3-112m^5+64m^7 \quad (22)$$

Resultant Matrix is $S_{p_5,p_7}(x_1)$ is a 10*10 matrix

$$r(x_1)=\det S_{p_5,p_7}(x_1) \quad (23)$$

It is a polynomial in x_1. It is found using Mathematica® 6 by Resultant command.

$$r(x_2) = 16777216 m^4 (m - x_1)^4 r_1^2 (x_1) \qquad (24)$$

Here, $r(x_2)$ is a 22nd order polynomial and $r(x_1)$ is a ninth order polynomial calculated by Mathematica® 6.

III. Jenkins-Traub Algorithm and ASE

The resultant theory with combination of Mathematica® 6 yields the required resultant of the polynomial. In order to predetermine the switching angles the resultant polynomial need a solution. Jenkins-Traub algorithm robust numerical algorithm, which can thoroughly deal with computer round-off errors, would provide the needed solution. It is a three-stage, extremely effective, globally convergent algorithm designed specifically for computing the roots of polynomials [25]. It uses the technique of deflation of the polynomial by synthetic division to find a root each time. This specific feature is fully utilized in solving the polynomial. The algorithm does not stop as the roots are computed; it proceeds to compute in the in similar way until all roots are exacted in increasing magnitude. This approach is taken because deflation of a polynomial can be unstable unless done by factors in order of increasing magnitude. The algorithm converges for any distribution of roots and the convergence is faster than the quadratic convergence of Newton-Raphson iteration. The entire process is implemented in VC++ platform, which can be understood through algorithms *A*.and *B*.detailed below.

A. Algorithm to generate x_1

(i) The first step involves the calculation of the coefficients of the equations for a given ‘*m*’ value. The program takes the ‘*m*’ value as the input from the user.

(ii) The next step is writing the values of the roots which are in the range of interest which is between 0 and 1. To do this the complex roots are to be effaced. Using appropriate ‘if’ conditions the imaginary roots are eliminated.

(iii) The negative roots and the roots which are greater than one are eliminated. The roots which satisfy all the conditions are written into a file named “x_{11}out.txt” along with the ‘*m*’ value. An “end of file marker” is also used for verification purposes.

B. Algorithm to generate x_2 and x_3

This also involves a similar process.

(i) The coefficients of the equations are calculated depending on both ‘*m*’ and ‘x_1’ values. The file’ x_{11}out.txt’ is opened in read mode and the ‘*m*’ value is extracted first. Following this the ‘x_1’ values are read one by one.

(ii) For each of the ‘x_1’ values the coefficients are calculated. The equations are solved using the same steps as above.

(iii) The ‘x_2’ values are also filtered using the same procedure. All the negative roots, the complex roots and roots greater than one are also discarded.

(iv) The ‘x_3’ values are calculated using the formula $x_{3=}$ $(m-x_1-x_2)$. The ‘x_3’ value has to be greater than ‘x_2’which in turn has to be greater than ‘x_1’. These conditions are checked using simple ‘if’ conditions.

(v) If all these conditions are satisfied then these roots are triplet roots.

A text file “x_{12}out.txt” is created to write the calculated values in append mode. The x_1, x_2 and x_3 values are written into the file. If they are triplet then it is indicated and the corresponding firing angles α_1, α_2 and α_3 are calculated and saved into the file.

The module is coded as a two-step process to monitor the working of the codes closely. The values that are being generated can be viewed at every step. If the first stage is found not working properly then the execution can be stopped and the process can be started from the beginning. Another advantage of the code is that even the non-triplet positive roots of the system are available in the file which can be used later if needed. The fastidious process of filtering gives surety of the results. One great advantage of the module is that it gives all the triplet roots for all the values of ‘*m*’ in a single file. Since the “x_{12}out.txt” is opened in append mode the results are in a detailed form. The algorithmic steps are indicated sequentially using a data flow diagram (DFD) in Fig.4. DFD will be able to provide a structural analysis of the software programme designed to solve the set of polynomial [23].

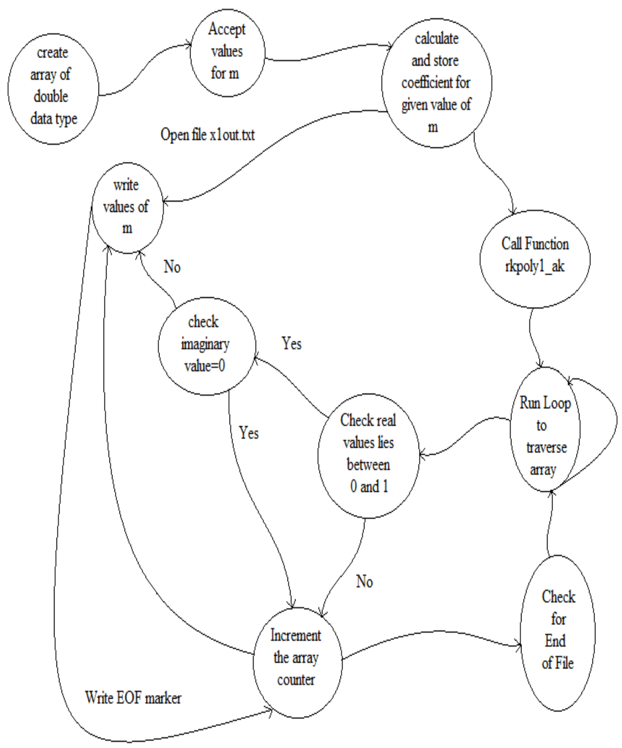

Fig. 4: Data flow diagram for computation of x_1.

IV. Simulation Results

The seven-level cascaded inverter is simulated using MATLAB/Simulink software. All the separate DC voltages are set equal voltage values of 50V. The predetermined switching angles calculated are used for selective harmonic elimination. Tables 2, 3 and 4 shows the summary of switching angle computed against elimination of specific harmonics pair. Table 5 clearly shows the comparison between N-R and Resultant method. Similar tables can be formed for any pair to be eliminated. The basic result, the variation of switching angles with respect modulation index for 5th and 7th harmonic elimination, is indicated in Fig.5. Fig.6 indicates the presence of harmonics before application of the Jenkin-Traub algorithm.

Table 2: Switching angle for elimination of 5rd and 7th Harmonics

MI	α_1	α_2	α_3	$\%V_5$	$\%V_7$	THD (%)
1.15	40.9	66.86	89.91	0.07	0.36	46.26
1.15	41.1	66.73	89.92	0.18	0.31	46.67
1.45	39.4	57.55	81.88	0.07	0.04	46.07
1.50	39.4	56.25	80.09	0.07	0.02	45.92
1.75	35.6	54.29	69.33	0.02	0.08	41.23
1.85	31.1	55.88	65.26	0.95	0.48	38.52
1.85	6.73	34.39	88.18	0.03	0.2	16.01
1.85	6.25	33.87	88.52	0.05	0.07	16.6
2.20	14.9	39.07	62.79	0.03	0.11	15.42
2.35	11.7	31.51	58.77	0.06	0.01	10.48
2.40	11.5	28.71	57.1	0.1	0.02	9.51
2.45	12	25.56	55.27	0.08	0.04	9.60
2.50	13.7	21.5	53.26	0.08	0.06	12.51

Table 3: Switching angle for elimination of 3rd and 5th Harmonics

MI	α_1	α_2	α_3	$\%V_3$	$\%V_5$	THD (%)
01.65	11.98	47.89	89.92	0.01	0.07	14.95
01.70	11.73	45.93	88.54	0.11	0.05	14.46
01.75	11.73	43.91	87.10	0.02	0.04	14.66
01.80	12.01	41.82	85.60	0.03	0.07	15.16
01.85	12.60	39.62	84.03	0.08	0.05	15.64
01.90	13.54	37.27	82.41	0.10	0.03	15.95
01.95	14.88	34.70	80.70	0.11	0.03	16.12
02.00	16.74	31.75	78.92	0.02	0.03	16.89

Table 4: Switching angle for elimination of 3rd and 7thharmonics

MI	α_1	α_2	α_3	$\%V_3$	$\%V_7$	THD (%)
01.70	16.58	42.81	89.53	0.01	0.12	14.35
01.75	14.19	42.47	87.53	0.16	0.07	13.79
01.80	11.88	41.89	85.58	0.08	0.01	15.16
01.85	09.55	41.13	83.64	0.03	0.08	16.11
01.90	07.10	40.23	81.70	0.03	0.03	16.69
01.95	04.21	39.22	79.74	0.08	0.07	18.39

Fig.7 clearly indicates the elimination of selected harmonics after the application of the algorithm. Besides the efficient cancellation of above mentioned harmonics and the total harmonic distortion (THD) is also reduced about 14.35% [29].

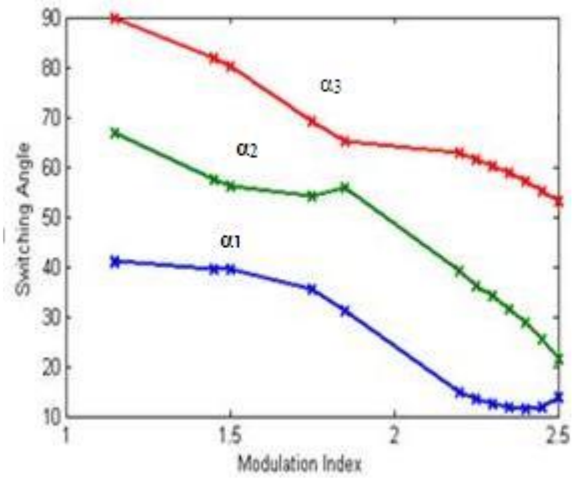

Fig. 5: Optimal switching angles versus MI for 5th and 7th harmonics elimination

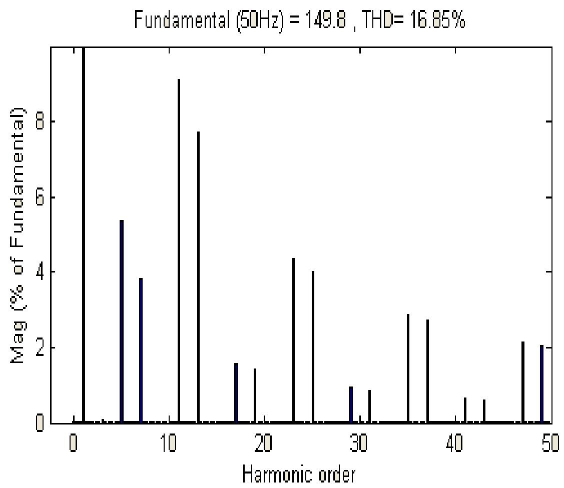

Fig.6: Harmonic spectrum without harmonic elimination

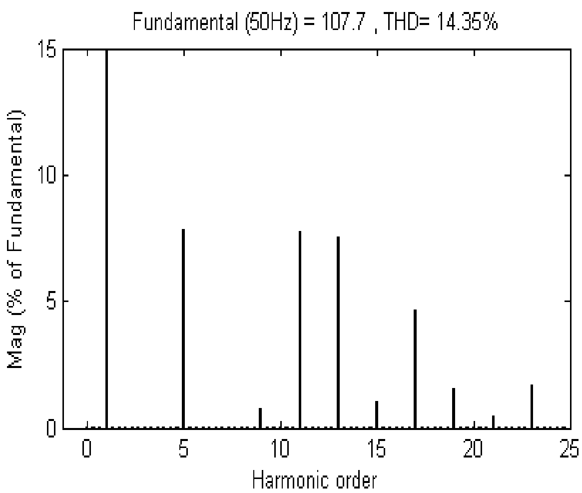

Fig.7: Output voltage and harmonic spectrum for (MI=1.7) with 3rd and 7th harmonic elimination

Table 5: Comparison of n-r method with proposed resultant theory method

Methods	MI	α_1	α_2	α_3	V_1 (V)	V_3	V_5	V_7	V_9	THD (%)
						(% of V_1)				
N-R Method	1.15	41.35	67.40	90	71.9	43.62	0.46	0.53	5.69	49.89
	1.45	39.42	58.05	82.49	89.61	42.44	1.05	0.83	7.03	47.43
	1.85	32.69	54.87	66.39	115.1	38.55	0.04	0.97	4.99	40.58
	2.3	12.35	33.81	60.11	146	5.74	0.07	0.70	3.84	14.08
Proposed Method (Resultant Theory)	1.15	40.9	66.86	89.91	72.88	42.90	0.04	0.48	5.14	48.18
	1.45	39.4	57.55	81.88	91.87	43.09	0.04	0.03	7.85	47.75
	1.85	31.1	55.88	65.26	115.7	36.23	1.16	0.91	9.55	39.83
	2.3	12.5	34.11	60.28	145.6	6.04	0.04	0.03	3.76	14.23

V. EXPERIMENTAL CORROBORATION

The constructed prototype hardware with the test work bench is shown as a photograph in Fig.8. The control circuit and power circuit of 7-level inverter is designed and fabricated. The switching angles are calculated in off-line for different operating conditions. Real-Time Windows Target of MATLAB/Simulink is used to generate the gating pulses.

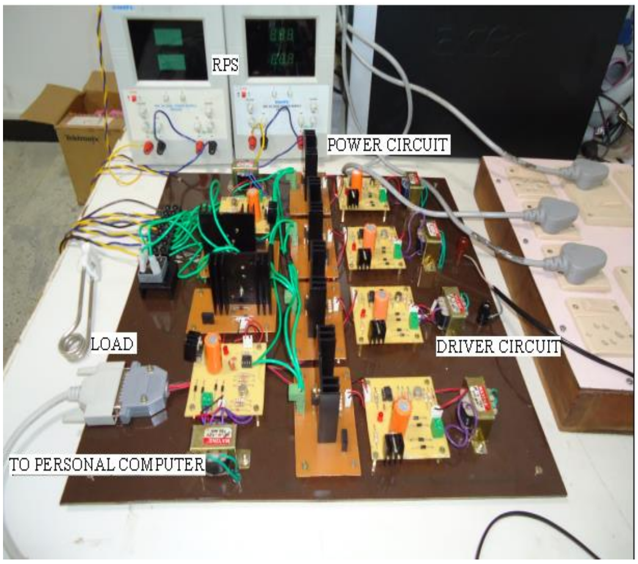

Fig.8: Photograph of the hardware setup

The host computer needs only a virtual device driver to exchange parameters between MATLAB and Simulink memory space. The Virtual Reality Toolbox contains functions for using special hardware devices, including Joystick and space-Mouse. It connects the hardware devices using Simulink blocks. The separate DC voltages are set to 50V and the resistive load is set to 100 ohms. MOSFETs IRF840 constitute the power module. The result for 5^{th} and 7^{th} harmonic elimination is studied in this section.

The systematic digital generation of gating pulses is displayed vividly through channels 1 to 4 of the scope TPS2024. A sample of the output voltage along with output current is captured through the two channels of the same scope as seen in Fig.9 and also demonstrates they in phase nature (for resistive load). The harmonic spectrum of output voltage and current is presented in Fig.10 and Fig.11 for MI=1.7.The experimental results closely agree with the simulation results as seen in Table 6.

Table 6: Comparison of simulated and hardware results (MI=1.7)

Methodology	Fundamental Voltage	V_3	V_7	THD (%)
		$\%V_1$		
Simulation Values	76.16	0.01	0.03	14.35
Hardware Values	76.62	.513	.527	17.40

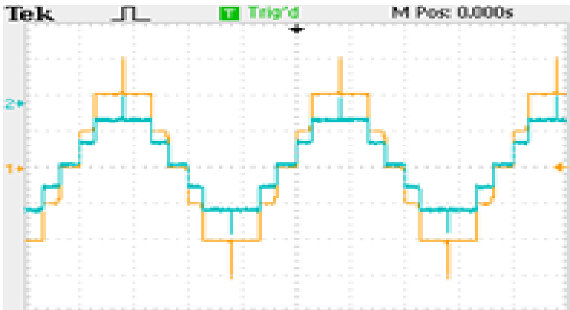

Fig.9: Output voltage and current waveform-R load

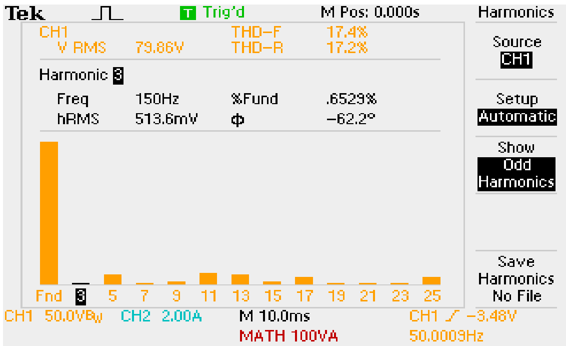

Fig.10: Harmonic spectrum of output voltage

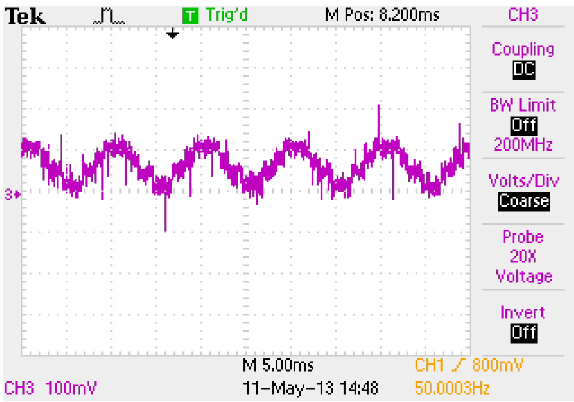

Fig.11: Harmonic spectrum of output current -RL load

VI. CONCLUSION

In recent years, multi-level inverters are widely used as static power converter for high power applications such as FACTS devices, high voltage DC (HVDC) transmission, ac drives, active filters, static var compensator and heavy duty hybrid-electric vehicles (HEVs) such as tractor trailers, transfer trucks, military vehicles. Even though the MLIs triumph in generating distortion less output voltages with reduced switching operation, dominant lower order harmonics restrict their application. Selective harmonic elimination can generate high quality output voltage through elimination specific order harmonics rather than shifting the harmonics to multiples of carrier frequency. The problem of eliminating harmonics in switching converters has been the focus of research for many years.

A systematic method is presented both through software simulation and hardware implementation to perform selective harmonic elimination is presented. The problem of selective harmonic elimination, together with voltage control, is formulated as Fourier analysis, simplified using resultant theory, reduced using Mathematica 6 and then solved by Visual C++ programme by calculation of all the possible triplent roots. The optimal switching angles obtained through the ASE not only eliminate the selected frequency components, but also guarantee a smaller total harmonic distortion (THD). The algorithm presented in this paper can be applied to MLI of any number of output levels and harmonics of any order. The developed ASE may be extended logically to three-phase system as well.

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