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Selective Harmonic Elimination for Multilevel Inverter in Statcom

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Abstract: The multilevel Inverter is a widely used for high power utility applications. To provide stepped sinusoidal waveforms with low harmonic content with reduced distortion. Improving the inverter performance means improving the quality of the output voltage. For this purpose a set of transcendental equations known as selective harmonic elimination equation is used for eliminating or reducing magnitude of desired harmonics. The required switching angles can be computed by solving the selective harmonic equations by using Newton-Raphson technique. The computed switching angles are then used for switching the switches used in the multilevel inverter of the STATCOM. The magnitude of the output waveform can be changed by changing the modulation index. By changing the value of modulation index the Total Harmonics Distortion (THD) also will change. In this paper, the performance of single phase full-bridge inverter using SHE scheme with varying the modulation index is evaluated in order to achieve a minimum THD.

I. INTRODUCTION

Multilevel inverters present the great advantage of harmonic reduction in the output waveform without increasing the switching frequency or decreasing the inverter output power. They are used in many industrial applications such as motor drives, renewable energy, power conditioners, active filters, Flexible AC Transmission System (FACTS), high voltage direct current lines and others .The output voltage waveforms of a multilevel inverter are composed of the number of levels of voltages and as the number of levels increases, the output THD decreases. The number of the achievable voltage levels, however, is limited by converter's complexity, voltage unbalance problems, voltage clamping requirement, circuit layout, and packaging constraints. There are essentially three types of multilevel inverters: i) cascaded H-bridges in which the number of levels grows according to the number of series-connected modules in the converter ii) Diode clamped that uses capacitors and diodes for inversion iii) Flying capacitor, in which the capacitors need to be pre-charged and is somewhat similar to diode clamped. The difference is that clamping is done through capacitors instead of diodes. Voltage characteristics of the cascaded multilevel inverters (CHB) are intrinsically better than two level converters, but further improvements can be achieved using specific modulation techniques based on analytical or numerical methods capable of harmonic elimination or mitigation . Unlike other multilevel inverter topologies, the cascade-type multilevel inverter is characterized by having a modular structure with less components. Harmonic content is one of the most important aspects of these inverters. The amount of harmonics, introduced to the system, is lesser as compared with those of common inverters because of the staircase waveform of multilevel inverters. However, some studies have concentrated on proposing an effective technique to reduce harmonic contents further, and as a result, different methods have emerged: sinusoidal Pulse Width Modulation (PWM), selective harmonic elimination (SHE), and Space Vector Modulation (SVM). However, PWM techniques are not able to eliminate low order harmonics completely. Another approach is to choose switching angles so that specific lower order dominant harmonics are suppressed. This method is known as Selective Harmonic Elimination (SHE) or programmed PWM technique in technical literatures. A fundamental issue associated with such method is to obtain the arithmetical solution of nonlinear transcendental equations that contain trigonometric terms and naturally present multiple solutions. SHE techniques offer several advantages over other modulation methods, including acceptable performance with low switching frequency to fundamental frequency ratios, direct control over output waveform harmonics, and the ability to leave triple harmonics uncontrolled to take advantage of circuit topology in three phase systems, and therefore have drawn great attention in recent years.

II. CASCADED HALF – BRIDGE DC LINK MULTILEVEL INVERTER WITH 4 DC SOURCES

Cascade Multilevel Inverter (CMLI) is one of the most important topology in the family of multilevel and multipulse inverters. It requires least number of components with compare to diode-clamped and flying capacitors type multilevel inverters and no specially designed transformer is needed as compared to multipulse inverter. It has modular structure with simple switching strategy and occupies less space.

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The CMLI consists of a number of H-bridge inverter units with separate dc source for each unit and is connected in cascade or series as shown in Fig. 1. Each H-bridge can produce three different voltage levels: +Vdc, 0, and –Vdc by connecting the dc source to ac output side by different combinations of the four switches S1, S2, S3, and S4. The ac output of each H-bridge is connected in series such that the synthesized output voltage waveform is the sum of all of the
individual H-bridge output.

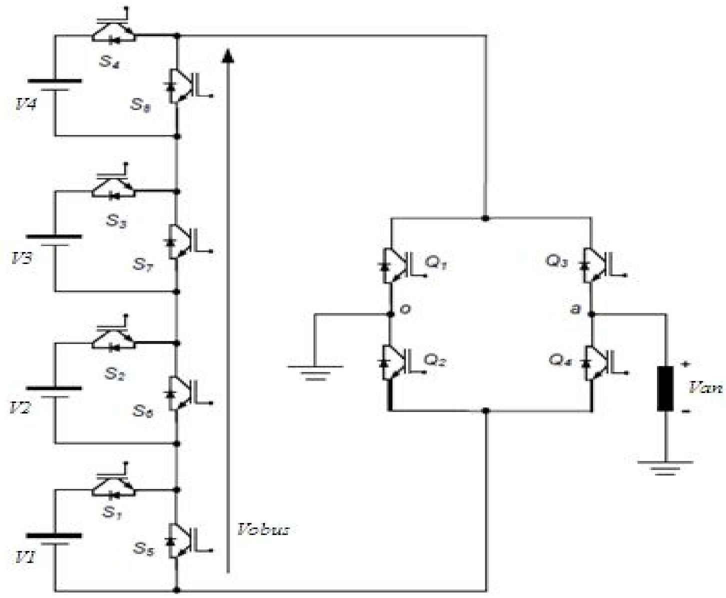

Fig.1. Configuration of single-phase H-bridge 9 level cascade multilevel inverter

By connecting the sufficient number of H-bridges in cascade and using proper modulation scheme, a nearly sinusoidal output voltage waveform can be synthesized. The number of levels in the output phase voltage is 2*s*+1, where *s* is the number of H-bridges used per phase. Fig.4 shows an 9-level output phase voltage waveform using five H-bridges.
The magnitude of the ac output phase voltage is given by Van $=V_{a1}+V_{a2}+V_{a3}+V_{a4}+V_{a5}$

Table:1 Switching pattern

State	Vbus	Switches in ON state
1	V_1	S_1,S_6,S_7,S_8
2	V_2	S_5,S_2,S_7,S_8
3	V_3	S_5,S_6,S_7,S_8
4	V_4	S_5,S_6,S_7,S_4
5	V_1+V_2	S_1,S_2,S_7,S_8
6	V_1+V_3	S_1,S_6,S_3,S_8
7	V_1+V_4	S_1,S_6,S_7,S_4
8	V_2+V_3	S_5,S_2,S_3,S_8
9	V_2+V_4	S_5,S_2,S_7,S_4
10	V_3+V_4	S_5,S_6,S_3,S_4
11	$V_1+V_2+V_3$	S_1,S_2,S_3,S_8
12	$V_2+V_3+V_4$	S_5,S_2,S_3,S_4
13	$V_1+V_2+V_4$	S_1,S_6,S_3,S_4
14	$V_1+V_2+V_4$	S_1,S_6,S_7,S_4
15	$V_1+V_2+V_3+V_4$	S_1,S_6,S_3,S_4

III. MATHEMATICAL MODELS OF SWITCHING ANGLES AND SHE EQUATIONS FOR A CASCADE MULTILEVEL INVERTER

These methods will cause extra losses due to high switching frequencies. For this reason, low switching frequency control methods, such as selective harmonic elimination method are used for modulation control. By placing notches in the output waveform at proper locations, certain harmonics can be eliminated. This allows lower switching frequencies to be used which led to
lower losses and higher efficiency.

A generalized quarter-wave symmetric stepped voltage waveform synthesized by 9 -level inverter is shown in Fig 1, where is the number of switching angles. By applying Fourier series analysis, the amplitude of any odd harmonic of the stepped waveform can be expressed as (2) whereas the amplitudes of all even harmonics are zero

$$V(t) = \sum_{n=1,3,5...}^{\infty} \frac{4V_{dc}}{n\pi}(\cos(ng_1) + \cos(ng_2) + \cos(ng_3) + ... + \cos(ng_s))\sin(n\omega t) \quad ....(1)$$

Where V is the level of dc voltage, n is an odd harmonic order, m is the number of switching angles, and gk is the Sth switching angle.

To minimize harmonic distortion and to achieve adjustable amplitude of the fundamental component, up to harmonic contents can be removed from the voltage waveform. In general, the most significant low-frequency harmonics are chosen for elimination by properly selecting angles among different level inverters, and high-frequency harmonic components can be readily removed by using additional filter circuits.

To keep the number of eliminated harmonics at a constant level, all switching angles must be less than. However, if the switching angles do not satisfy the condition, this scheme no longer exists. As a result, this modulation strategy basically provides a narrow range of modulation index, which is its main disadvantage. For example, in a seven-level equally stepped waveform, its modulation index is only available from 0.5 to 1.05. At modulation indexes lower than 0.5, if this scheme is still applied, the allowable harmonic components to be eliminated will reduce from 2 to 1. The total harmonic distortion (THD) increases correspondingly.

From harmonic elimination theory the harmonic equation is

$$\cos(ng_1) + \cos(ng_2) + \cos(ng_3) + ... + \cos(ng_s) = 0 \quad ....(1)$$

Where n=1, 5, 7 and s which represents number of dc sources. The objective of SHE is to eliminate lower order harmonics while remaining harmonics can be removed with filter. In this paper, a 9-level cascaded multilevel inverter is taken to eliminate seventh and ninth harmonics. So, to satisfy the fundamental harmonic component and eliminate the seventh and ninth harmonics, three nonlinear equations with three angles are provided in

$$\cos(g_1) + \cos(g_2) + \cos(g_3) = \frac{\pi V_1}{4V_{dc}} \quad .... (2)$$

$$\cos(5g_1) + \cos(5g_2) + \cos(5g_3) = 0 \quad .... (3)$$

$$\cos(7g_1) + \cos(7g_2) + \cos(7g_3) = 0 \quad .... (4)$$

$$\cos(9g_1) + \cos(9g_2) + \cos(9g_3) = 0 \quad ....(5)$$

The equation 2 can be written as

$$\cos(g_1) + \cos(g_2) + \cos(g_3) = m \quad .... (6)$$

When

$$m = \frac{\pi V_1}{4V_{dc}}$$

Multiples of 3rd harmonics are eliminated in line to line three phase system.

To eliminate seventh and ninth harmonic V7 and V9 are set to zero in the above equation. To determine the switching angles the following equations must be solved, Here M represents modulation index varies from 0 to 1.

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IV. SOLUTION USING NEWTON-RAPHSON METHOD

The Newton-Raphson (N-R) method is one of the fastest iterative methods. This method begins with an initial approximation and generally converges at a zero of a given system of nonlinear equations

The N-R method is to be implemented to compute the switching angles for the system given by . The Switching angles which are in the range of 0 to π/2 producing desired fundamental voltage along with elimination of 5th ,7th, 11th, and 13th harmonic components for a given modulation index are feasible solutions . The N-R method implemented previously based on trial and error method for estimation of initial guess and m*I* for which solutions exist.

Once a solution set was obtained, successive solutions were computed by using previous solution set as initial guess for the next one; proceeding in this way, only one solution set was obtained. Here, the N-R method is implemented in a different way for which an arbitrary initial guess between 0 to π/2 is assumed and switching angles (keeping all switching angles in the feasible range) along with the error (% content of 5th, 7th, 11th, and 13th harmonic components) are computed for complete range of m*I* by incrementing its value in small steps (say 0.001).

The different solution sets are obtained for a particular range of m*I* where they exist i.e. the error is zero for feasible solutions shown in fig 2 ;after getting preliminary solution sets, complete solution sets are computed by using known solutions as initial guess. Now a basic question is how one can assure that all solution sets have been obtained. The answer is simple, as initial guess is randomly chosen so it has nothing to do with any particular solution set i.e. there is equal chance for each solution set to occur if they exist.

A. The Algorithm for the Newton-Raphson Method is as follows

1) Assume any random initial guess for switching angles (say α0) Such that 0< α1< α2<….. α5< π/2.
2) Set m*I*=0.
3) Calculate F(α0),B(m*I*) and Jacobian J(α0).
4) Compute correction Δα during the iteration using relation Δα=J-1(α0)*(B(m*I*)-F(α0))
5) Update the switching angles i.e, α(k+1)= α(k)+ Δα(k)
6) Perform α(k+1)=cos-1 (abs(cos(α(k+1))) transformation to bring switching angles in feasible range.
7) Repeat steps (3) to (6) for sufficient number of iterations to attain error goal.
8) Increment m*I* by a fixed step.
9) Repeat steps (2) to (8) for whole range of m*I*.
10) Plot the switching angles as a function of m*I*. Different solution sets would be obtained.
11) Take one solution set at a time and compute complete solution set for the range of m*I* where it exits.

By following the above steps, all possible solution sets, when they exist, can be computed without any computational complexity.

B. Nine (9) Level CMLI

By using selective harmonics elimination method possible outcomes for nine level inverters are calculated ,mi is the gating angles, tables below shows the angels for deferent mi and the graph is plotted

Table 2 : SWITCHING ANGLES DETERMINED for different modulation index for 9 and 11 levels

Mi	g_1	g_2	g_3	g_4
0.4	37.23	58.82	75.48	89.97
0.44	36.17	55.97	71.92	89.99
0.49	34.58	53.00	66.18	87.42
0.55	32.16	51.95	59.44	81.65
0.6	19.45	45.43	54.74	80.46
0.66	18.66	43.32	52.45	73.22
0.69	15.80	38.79	51.58	70.34
0.74	11.10	31.41	47.32	66.97
0.79	6.67	25.68	40.12	63.25
0.83	0	0	0	0

Mi	g_1	g_2	g_3	g_4	g_5
0.4	0	0	0	0	0
0.44	0	0	0	0	0
0.49	33.49	53.02	62.76	82.14	88.82
0.55	32.67	51.29	60.62	79.52	89.98
0.6	31.67	49.48	57.86	74.08	89.60
0.66	30.82	47.00	56.16	67.57	85.77
0.69	30.67	45.33	56.59	63.73	82.56
0.74	28.76	46.02	50.29	64.06	73.02
0.79	9.78	28.02	44.29	62.05	87.18
0.83	7.35	23.35	38.74	58.32	87.05

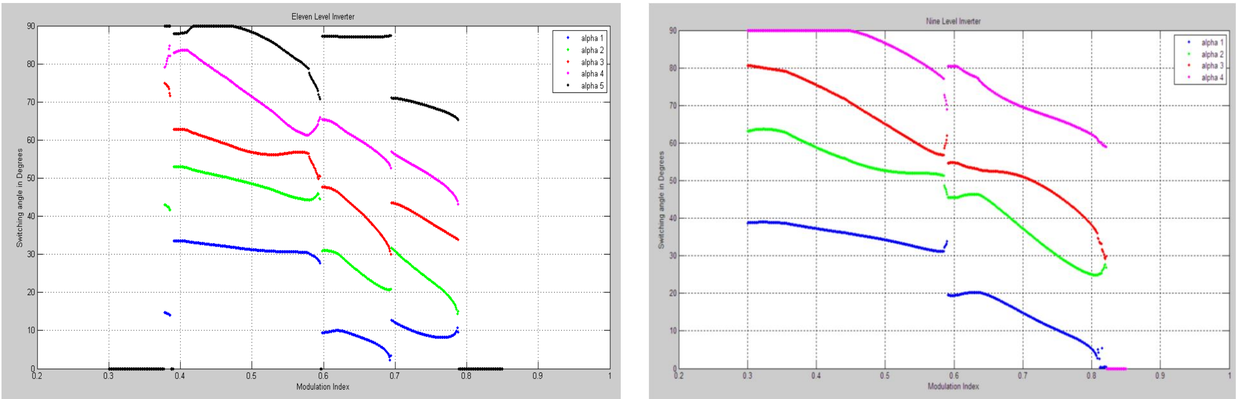

Fig: 2 Plot of switching vs Modulation Index for 11-level inverter and 9- level

V. SIMULATION RESULTS

Selective harmonic elimination technique is used for finding different angles that can be used for removing certain harmonic from the output waveform of the MLI. Newton Raphson is one such technique for finding the angles. To validate the obtained results simulation where carried out on Cascaded Half Bridge MLI and harmonic analysis is carried out to find the percentage content of selected harmonic in the output waveform The harmonics that are considered for elimination are 5th, 7th, 9th and 11th.

A. Harmonic Analysis of 9-Level Cascaded Half Bridge MLI.

The considered modulation index values are 0.6, and 0.8. It also gives the number of iteration required for obtaining the values. Fig 4 gives the output voltage waveforms of 9-Level MLI. Fig 5 gives the harmonic contents in different waveforms. Table 3 gives the percentage harmonic contents of 5th, 7th, 9th and 11th. It also gives the total harmonic distortion and RMS value of output voltage waveform of the inverter

Table:3 Selected Harmonic Content, THD and Vrms for different Modulation Index of 9-Level MLI

SL No.	*Modulation Index*	*% of 3rd Harmonic*	*% of 5th Harmonic*	*% of 7th Harmonic*	*% of 9th Harmonic*	*% of 11th Harmonic*	*%THD*	*Vrms*
1.	*0.5*	*40.44*	*1.07*	*0.95*	*0.78*	*2.03*	*43.38*	*130.6*
2.	*0.6*	*22.83*	*0.06*	*0.11*	*0.04*	*11.50*	*27.43*	*161.3*
3.	*0.7*	*17.27*	*0.00*	*0.01*	*0.12*	*1.84*	*20.58*	*185.1*
4.	*0.8*	*1.97*	*0.01*	*0.00*	*0.00*	*5.63*	*10.18*	*212.9*

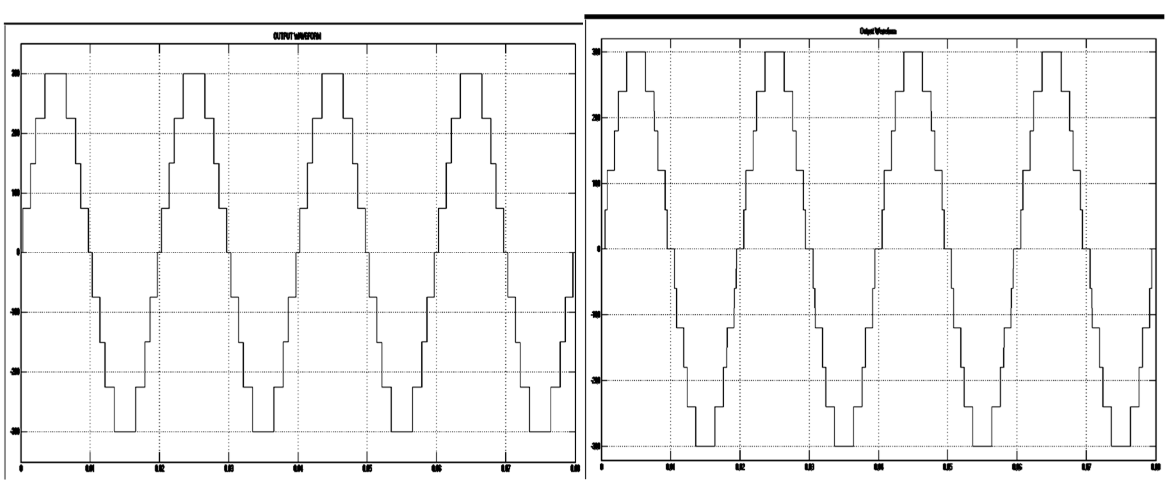

Fig:4 Output voltage waveform of 9-level MLI with 0.6 and 0.8 modulation index

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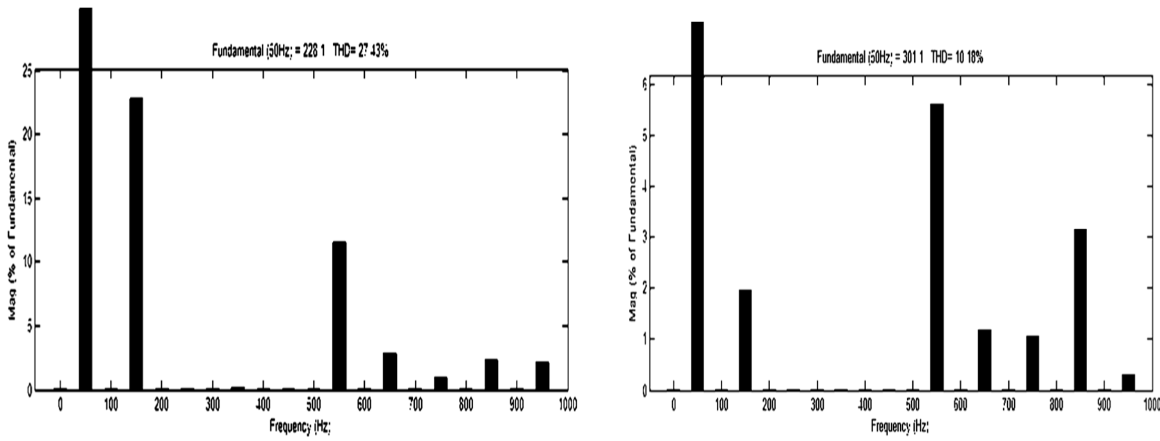

Fig:5 Harmonic content in Output voltage waveform of 9-level MLI with 06 and 0.8 modulation index

B. Harmonic Analysis of 11-Level Cascaded Half Bridge MLI.

The considered modulation index values are 0.5, 0.6, 0.7 and 0.8. It also gives the number of iteration required for obtaining the values. Fig 6 gives the output voltage waveforms of 11-Level MLI. Fig 7 gives the harmonic contents in different waveforms. Table 4 gives the percentage harmonic contents of 5^{th}, 7^{th}, 9^{th} and 11^{th}. It also gives the total harmonic distortion and RMS value of output voltage waveform of the inverter.

Table 4 Selected Harmonic Content, THD and Vrms for different Modulation Index of 11-Level MLI

SL No.	Modulation Index	% of 3^{rd} Harmonic	% of 5^{th} Harmonic	% of 7^{th} Harmonic	% of 9^{th} Harmonic	% of 11^{th} Harmonic	%THD	Vrms
1.	0.5	38.55	0.11	0.12	0.13	0.11	40.51	130.4
2.	0.6	11.94	2.21	0.07	1.33	0.69	16.50	161.1
3.	0.7	16.47	0.15	0.32	0.00	0.25	18.71	186.0
4.	0.8	1.87	0.22	0.02	0.37	0.74	9.34	212.2

Fig:6 Output voltage waveform of 11-level MLI with06 and 0.8 modulation index

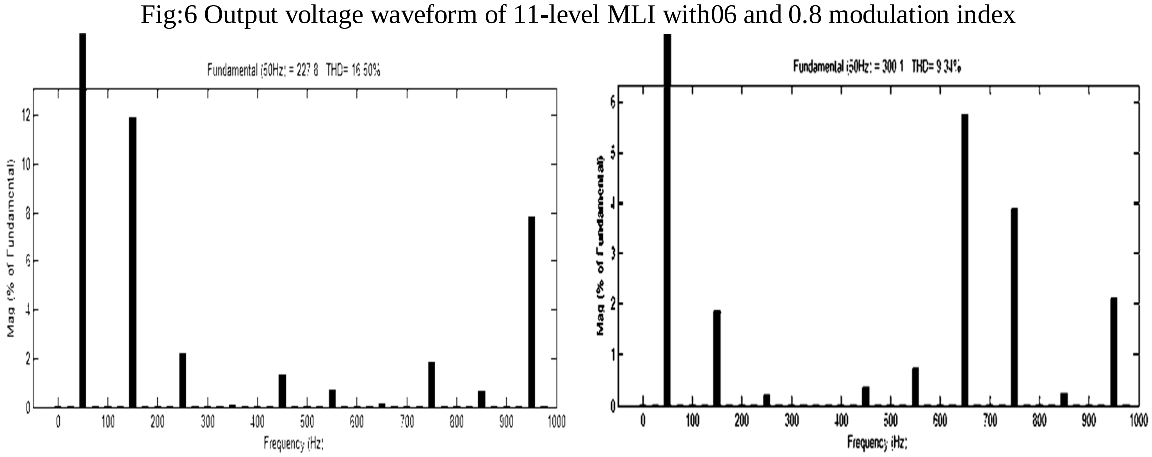

Fig:7 Harmonic content in Output voltage waveform of 11-level MLI with 0.6 and 0.8 modulation index

We can see the decrease in harmonic content and RMS value increases as levels increase for particular modulation index Thus it can be concluded that SHE technique successfully removes targeted undesired harmonics from the output voltage waveform of the MLI. It can successfully calculate the angles where notches are required to remove the targeted harmonics.

Table 5.7 Comparison of %THD, Vrms voltages of different Levels of MLI and Modulation index

SL No.	Modulation Index	7-level %THD	9-level %THD	11-level %THD	7-level Vrms	9-level Vrms	11-level Vrms
1.	0.5	47.95	43.38	40.51	127.0	130.6	130.4
2.	0.6	43.47	27.43	16.50	156.5	161.3	161.1
3.	0.7	25.45	20.58	18.71	184.2	185.1	186.0
4.	0.8	13.30	10.18	9.34	210.8	212.9	212.2

CONCLUSION

The selective harmonic elimination method at fundamental frequency switching scheme has been implemented using the Newton-Raphson method that produces all possible solution sets when they exist. In comparison with other suggested methods, the proposed technique has many advantages such as: it can produce all possible solution sets for any numbers of multilevel inverter without much computational burden; speed of convergence is fast etc. The proposed technique was successfully implemented for computing the switching angles for 9 levels and 11 levels CMLI.

A complete analysis for n - level inverter can be made and switching angle which results in lower THD and can be determined .SHE method can be calculated with other optimization techniques

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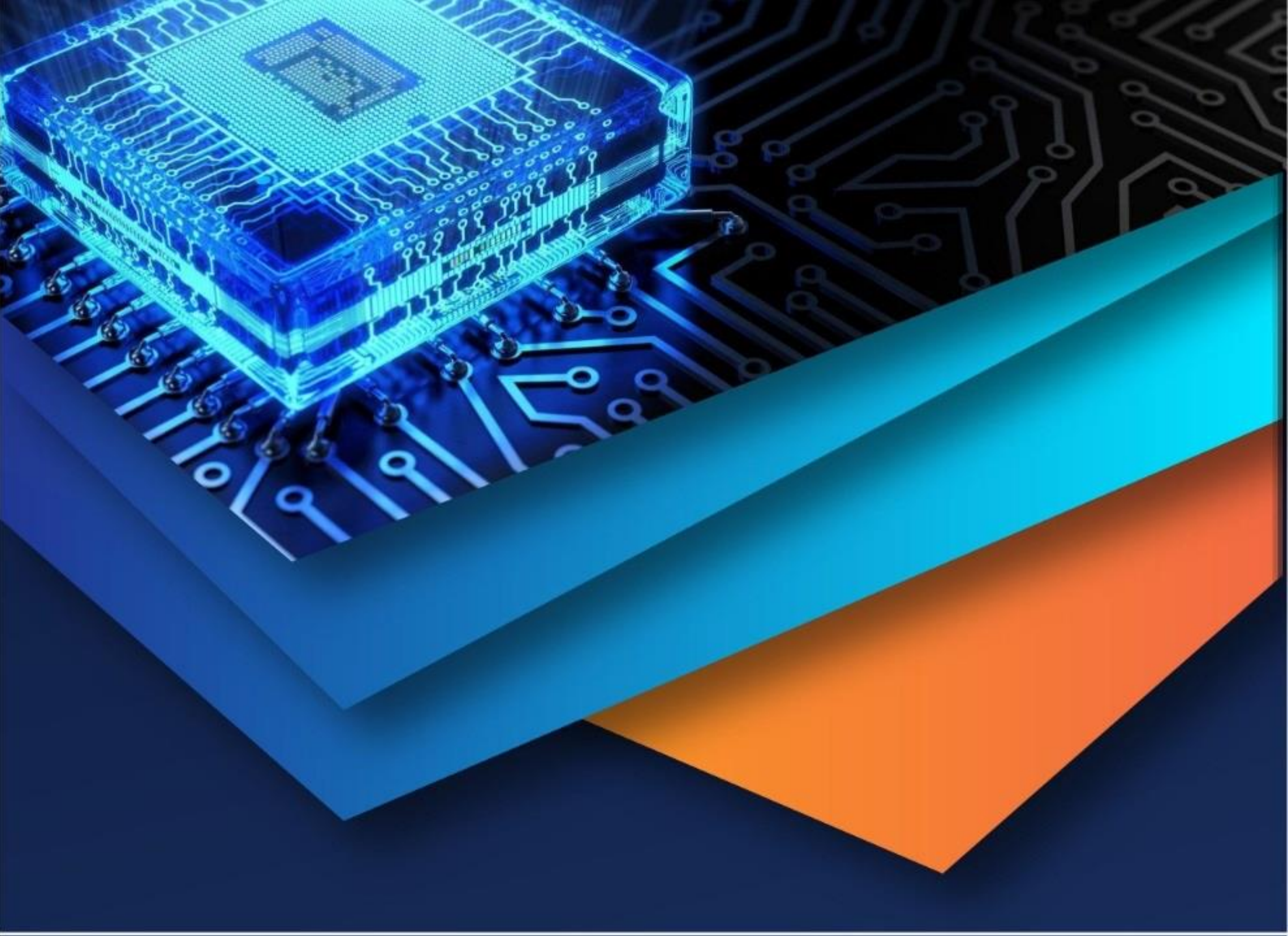

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