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Control of Output Voltage with Elimination of Four Lower Order Harmonics in Single Phase Eleven-Level Cascaded H-Bridge Inverter

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Abstract: *Ordinary single-phase or three phase two-level inverter gives a square wave output which when applied to electrical device may change its properties as the inverter output waveform is not sinusoidal rather contains lower and higher order harmonics in addition to fundamental. Moreover, the output voltage cannot be controlled. Although the output voltage waveform of these inverters can be improved by selecting specific switching angles of power semiconductor devices using SHEPWM technique for elimination of lower order harmonics with some obvious limitations. On the other hand, for a multilevel inverter, output voltage waveform can be synthesized in an easier way with systematic switching of semiconductor devices to achieve better performances than a two-level ordinary inverter. In spite of these technical improvement, although it is possible to achieve almost a sinusoidal voltage waveform depending upon the number of levels but the inverter output voltage cannot be controlled. In this paper an idea is proposed by which a single phase 11-level inverter can be implemented using cascaded H-bridges with elimination of lower order harmonics and with adjustable output voltage. This idea can be extended to develop three phase CHMLI inverters with adjustable output voltage.*

Keywords: *Harmonic Factor (HF), inverter, power semiconductor devices, SHE-PWM technique, simulation, total harmonic distortion (THD), transcendental equation.*

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I. Introduction

For an 11-level cascaded H- bridge inverter, the number of H-bridges required is 5 (vide Fig. 1) and all the H-bridges are connected in cascade. Each H-bridge is considered as 3-level inverter as shown in Fig. 2). The output voltage waveform for 11-level inverter is shown in Fig. 3[1,2,3,4].

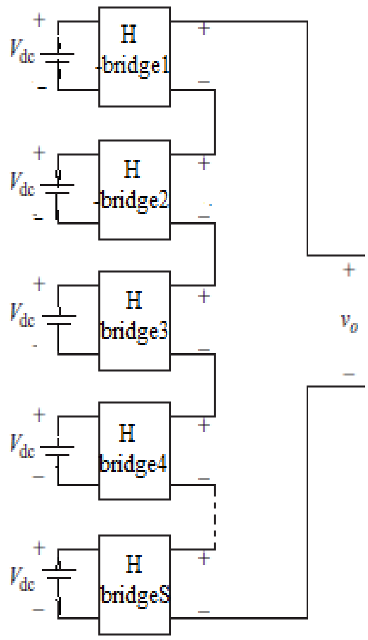

Fig.1: Multilevel Inverter with S no H-bridges.

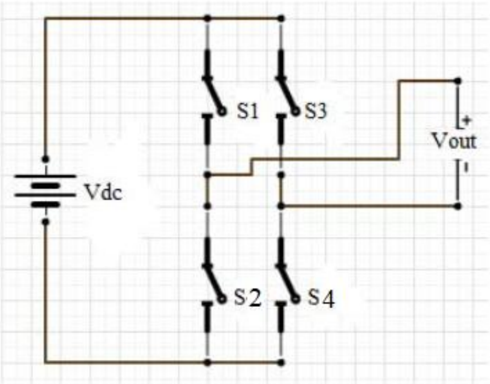

Fig.2(a). Circuit diagram of a three-level inverter

Table no 1: Switching condition and output

Switch Condition	Output
S1 and S4 closed	+Vdc
S3 and S2 closed	-Vdc
Either S1 and S3 or S2 and S4 are closed	OV

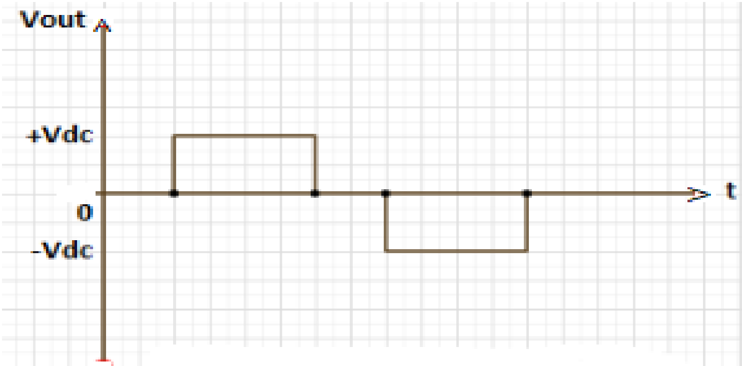

Fig.2(b). Voltage waveform of three-level inverter or a single H-bridge

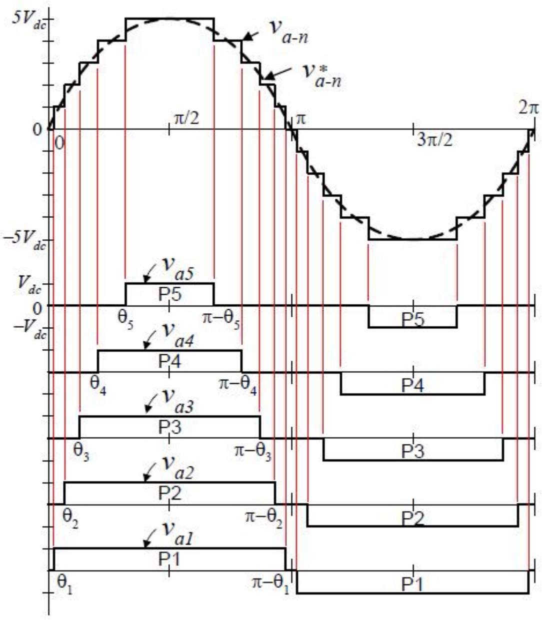

Fig. 3: Output voltage waveform of 11-level CHMLI

II. Expression for Output Voltage of 11-level Inverter

For 11-level inverter having 5 number of H-bridges, using Fourier series, the general expression for the instantaneous output voltage can be expressed as[5,,6,7,8]

$$V_0(t)= \frac{4V_{dc}}{n\pi}\sum_{n=1,3,5,7,....}^{\propto}[\cos(n\theta_1) + \cos(n\theta_2) + ... + \cos(n\theta_5)] \sin(n\omega t)...... (5)$$

Where 'n' is order of harmonics and n=1, 3, 5, 7,……∞ (Due to quarter wave symmetry of output waveform) and

$\theta_1, \theta_2, \theta_3, \theta_4$ and θ_5 are the switching angles of the 1st, 2nd, 3rd, 4th and 5th H-bridge respectively and $0 < \theta_1 < \theta_2 < \theta_3 .... < \theta_5 < \pi/2$.

III. Elimination of Lower Order Harmonics

To eliminate 3rd, 5th, 7th and 9th harmonics the equations to be solved for obtaining above switching angles are

$$[\cos(\theta_1)+ \cos(\theta_2)+ \cos(\theta_3)+ \cos(\theta_4)+ \cos(\theta_5)] - 5M = 0 = F_1(\theta) ..... (1)$$

and

$$[\cos(3\theta_1)+ \cos(3\theta_2)+ \cos(3\theta_3)+ \cos(3\theta_4)+ \cos(3\theta_5)] = 0 = F_2(\theta) ..... (2)$$

$$[\cos(5\theta_1)+ \cos(5\theta_2)+ \cos(5\theta_3)+ \cos(5\theta_4)+ \cos(5\theta_5)] = 0 = F_3(\theta) ..... (3)$$

$$[\cos(7\theta_1)+ \cos(7\theta_2)+ \cos(7\theta_3)+ \cos(7\theta_4)+ \cos(7\theta_5)] = 0 = F_4(\theta) ..... (4)$$

$$[\cos(9\theta_1)+ \cos(9\theta_2)+ \cos(9\theta_3)+ \cos(9\theta_4)+ \cos(9\theta_5)] = 0 = F_5(\theta) ..... (5)$$

Equation (1) will determine the amplitude of fundamental and equation (2), (3), (4) and (5) will be used to eliminate 3rd, 5th, 7th, and 9th harmonics from the output voltage waveform[9,10,11].

Table no 2: Switching angles for single phase 11-level cascaded multilevel inverter (CHMLI) with different modulation index obtained using GA optimization technique[12,13].

Modulation Index, M	Switching Angles (In Degrees)				
	θ_1	θ_2	θ_3	θ_4	θ_5
0.5	**12.52**	**27.0**	**55.0**	**86.0**	**88.50**
0.6	**12.10**	**24.0**	**42.60**	**68.37**	**86.78**
0.7	**11.5**	**22.5**	**34.0**	**52.5**	**74.0**
0.8	**8.0**	**18.15**	**29.12**	**39.1**	**63.13**
0.9	**5.25**	**16.37**	**31.1**	**43.0**	**62.67**

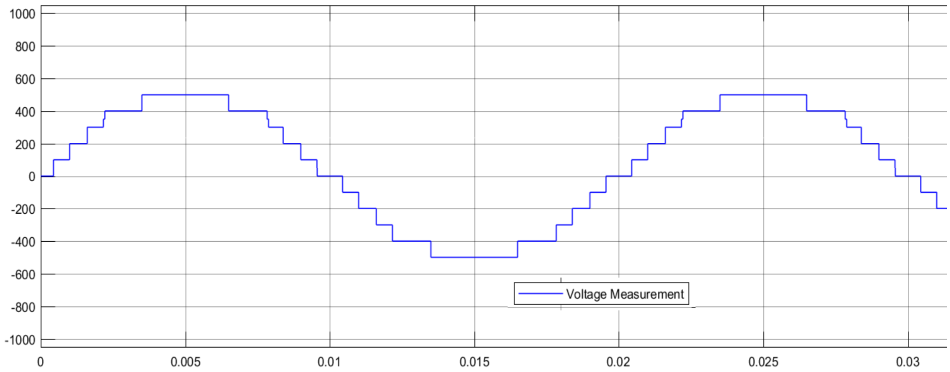

Fig. 4: Output voltage waveform of Two-level SHE-PWM inverter (without filter)

IV. Proposed Technique to Control Output Voltage in 11-Level Inverter

Figure 5(a) shows a common half-bridge inverter circuit which is a part of 11-level inverter. By systematic switching of five numbers of such half-bridge inverter using the above switching angles it is possible to eliminate 3rd, 5th, 7th and 9th lower order harmonics.

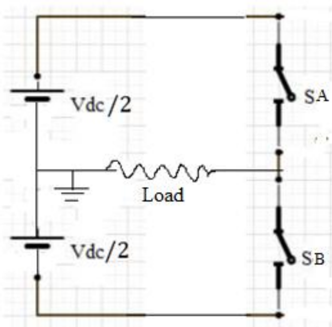

Fig. 5(a): A common half-bridge inverter

If two more power switches SX and SY are connected with each such half bridge inverter as shown in figure 5(b) to convert each half bridge to a full bridge or H-bridge and switching angle of each SX and SY are phase shifted by ∅, then it is possible to reduce the output voltage as per requirement. Maximum output voltage will be available when there is no phase shift and zero output voltage is available with 180° phase shift[14].

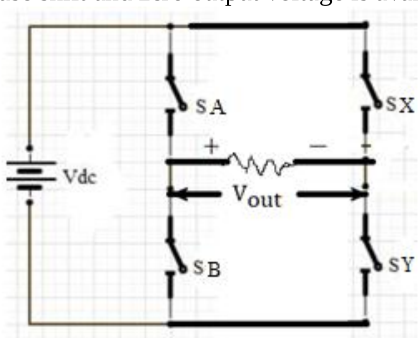

Fig.5(b). Circuit diagram of a three-level or H-bridge inverter

The amplitude of the output voltage as a function of fundamental frequency and odd harmonics for a phase-shifted single-phase 11-level inverter can be expressedas

$$V_o(t) = \frac{4V_{dc}}{n\pi} \sum_{n=1,3,5....}^{\infty} [\cos(n\theta_1) + cos(n\theta_2) + cos(n\theta_3) + cos(n\theta_4) + \ cos(n\theta_5)]$$

The amplitude of the output voltage for the fundamental frequency of a phase-shifted single-phase 11-level inverter can be expressed as

$$V_1 = \left[\frac{4V_{dc}}{\pi}\right] \times [\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4) + \cos(\theta_5)] \times [\cos(\varphi_1/2) + \cos(\varphi_2/2) + \cos(\varphi_3/2) + \cos(\varphi_4/2) + \cos(\varphi_5/2)]$$

Where, $\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5,$ are respectively the phase shift of H-bridge 1,H-bridge 2, H-bridge 3, H-bridge 4 and H-bridge 5 of the single-phase 11-level inverter for each SX and SY of every H-bridge. This idea can be extended for the adjustment of output voltage for three-phase 11-level inverter where lower order non-tripple'n' harmonics 5^{th}, 7^{th}, 11^{th} and 13^{th} will also be eliminated using SHEPWM.

V. SIMULATION & RESULTS

Results so obtained after simulation of the proposed system using MATLAB have been depicted in Table no 3.

Table no 3: 11-level inverter output voltage with phase shifting of different H-bridges

Phase Shift for	**Inverter output voltage for different phase shift (In Volt)**						
	Phase Shift 0^o	Phase Shift 30^o	Phase Shift 60^o	Phase Shift 90^o	Phase Shift 120^o	Phase Shift 150^o	Phase Shift 180^o
H-bridge 5. No PS for other Bridges	514.9	511.3	501.2	486.7	472.2	461.3	457.1
H-bridge 5, 4. No PS for other Bridges	514.9	451.2	434.4	410.5	385.2	365.5	358.4
H-bridge 5, 4, 3. No PS for other Bridges	514.9	352.2	334.4	308	279.1	256.2	247.3
H-bridge 5, 4, 3, 2. No PS for H-bridge 1	514.9	241	223.4	195.9	164.9	137.8	126.2
All H-bridges	514.9	121.7	109.1	88.96	62.58	32.43	0.3877

VI. Conclusion

Simulation has been made using MATLAB 2017a. During simulation different phase shifts have been considered for H-bridges 1 to 5. When 180^o phase shift were considered for each H-bridgesimultaneously for switches 3 and 4 of each H-bridge, theoretically the output voltage for the fundamental frequency should have been zero but due to approximate selection of firing angles, a very small voltage has been observed present after simulation.

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