Simulation of Cascaded H-Bridge Multilevel Inverter using OHSW PWM for the elimination of harmonics

Dr. M.S.Sivagama Sundari

Assistant Professor, Department of EEE, Amrita College of Engineering and Technology, Nagercoil, TamilNadu, India

Corresponding author: mssivagamasundari@gmail.com

Abstract: In this paper, an Optimized Harmonic Stepped Waveform (OHSW) technique was developed for harmonic elimination in a single phase cascaded h-bridge multilevel inverter. The particle swarm optimization procedure was utilized for evaluating the switching angles. As a novelty, so as to keep up the power balance among the various sources, a cyclic choice strategy is embraced that over a period of operation also the sources similarly contribute for the output power. A simulation in the MATLAB/SIMULINK platform has validated the proposed idea. A prototype was developed and the observations validated the proposed idea that eliminated the lower order harmonics. The harmonic spectrum and output waveforms were acquired for OHSW PWM method and existing Genetic algorithm.

Keywords: Multilevel inverter, Cascaded H-Bridge multilevel inverter, Total Harmonic Distortion, Optimized Harmonic Stepped Waveform (OHSW), MATLAB

1. Introduction

Multilevel inverters play a significant role in various applications such as medium-voltage drives, renewable energy system, grid interfaces, flexible AC transmission devices, static var compensation, dynamic voltage restoration, harmonic filtering, high voltage dc back-to-back intertie etc. In recent years, multilevel inverters have become more attractive for researchers and manufacturers due to their advantages over conventional three-level pulse width-modulated (PWM) inverters. They offer improved output waveforms, smaller filter size, lower EMI, lower total harmonic distortion (THD), and others[1]–[8].The three common topologies for multilevel inverters are as follows: 1) diode clamped (neutral clamped) [9]–[11]; 2) capacitor clamped (flying capacitors) [12]–[14]; and 3) cascaded H-bridge inverter [15]–[17]. In addition, several modulation and control strategies have been developed or adopted for multilevel inverters, including the following: multilevel sinusoidal (PWM), multilevel selective harmonic elimination, and space vector modulation.

Depending upon switching frequency the modulation strategies are classified into low switching frequency (fundamental switching frequency) and high switching frequency. High switching frequency methods employ switching frequency in order of several kHz. The major advantage of PWM methods employing much higher frequencies concerns harmonics but some times higher frequency causes undesirable harmonics where filtering is much easier and less expensive. Also, there is no power dissipation because generated harmonics might be above the band width of actual systems. But high switching frequency leads to high switching losses there by less converter efficiency, especially when used in high power applications. Fundamental switching frequency results in less switching losses and less thermal losses, which results high converter efficiency. This method is best suited for medium voltage drives. However, this method produces lower order of harmonics [3], [18].

A typical single-phase nine-level inverter adopts full-bridge configuration by using approximate sinusoidal modulation technique as the power circuits. The output voltage then has the following three values: zero, positive (+Vdc), and negative(−Vdc) supply dc voltage (assuming that Vdc is the supply voltage). The harmonic components of the output voltage are determined by the carrier frequency and switching functions. Therefore, their harmonic reduction is limited to a certain degree [4]. The cascaded H-bridge multilevel inverter needed a separate DC source for individual H-bridge and have been used for high power and high voltage applications. Also this topology is suitable for medium and large grid-connected PV systems [19-20]. In solar photovoltaic fed fifteen level CMLI [21], an optimized harmonic stepped waveform technique is introduced to eliminate lower order harmonics. In eleven level inverter [22-23], optimum relevance has been found out between switching angles and dc voltages to achieve minimum THD.

To overcome this limitation, this paper presents an eleven-level inverter whose output voltage can be represented in eleven levels. As the number of output levels increases, the harmonic content can be reduced. In this paper, an optimized harmonic stepped waveform technique (OHSW) is used to eliminate low-order harmonics in PV source fed eleven level CMLI, as well as to satisfy the fundamental amplitude.

2. Cascaded H-bridge eleven level Inverter topology

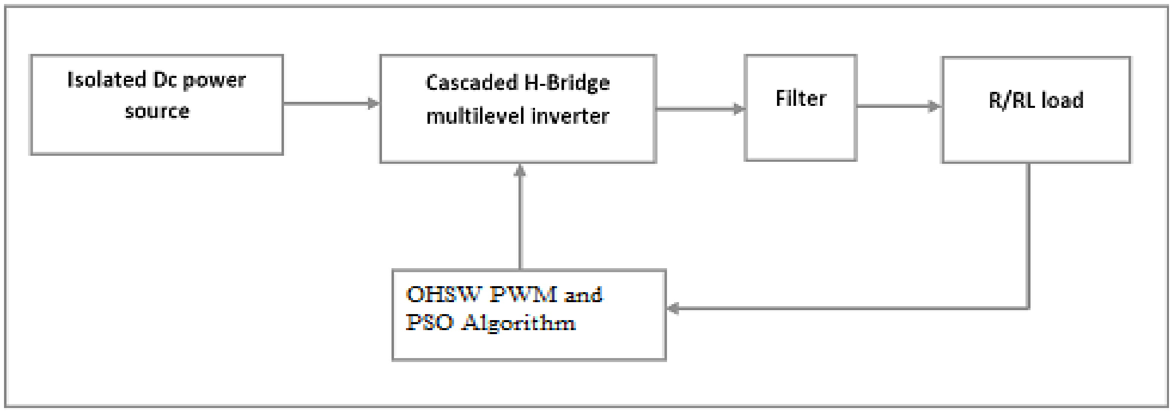

Fig.1 Block diagram of Cascaded H-bridge inverter topology

The block diagram of proposed Cascaded H-bridge inverter topology is shown in figure.1. This system consists of a multilevel DC/AC power inverter, filter and a load. The isolated dc power sources are connected to the Cascaded H-bridge inverter. The output of the cascaded inverter is ac voltage which is connected to load through filter. The load is considered as resistive and an inductive. Particle Swarm Optimization algorithm is employed for solving the non-linear objective function and finding out the optimal switching angles for the multilevel inverter switches. The objective of OHSW PWM is lower order harmonics elimination, while the fundamental component amplitude is satisfied.

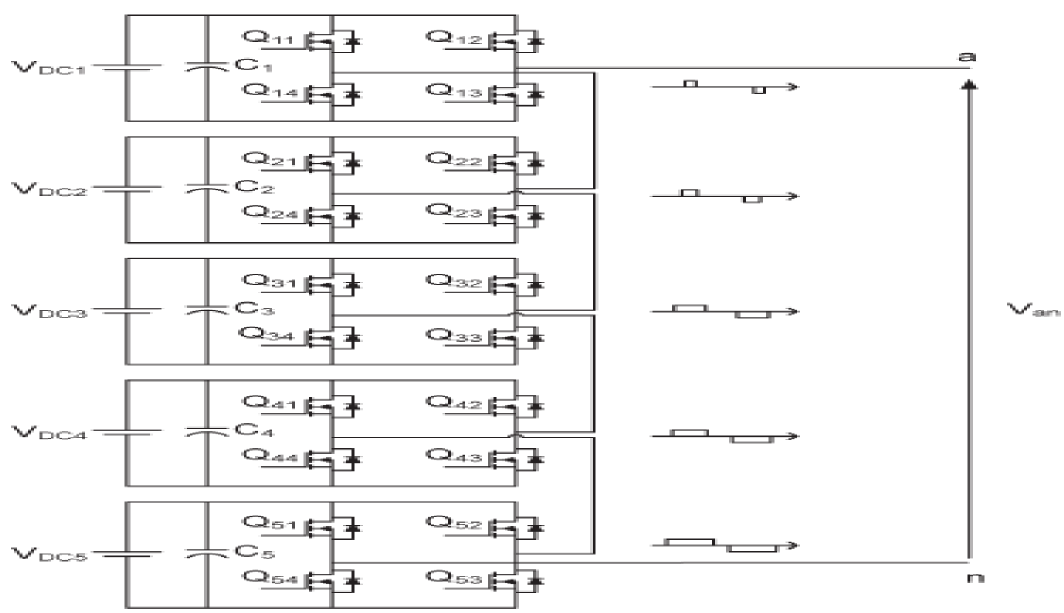

Fig. 2. Schematic of a single-phase cascaded eleven level inverter

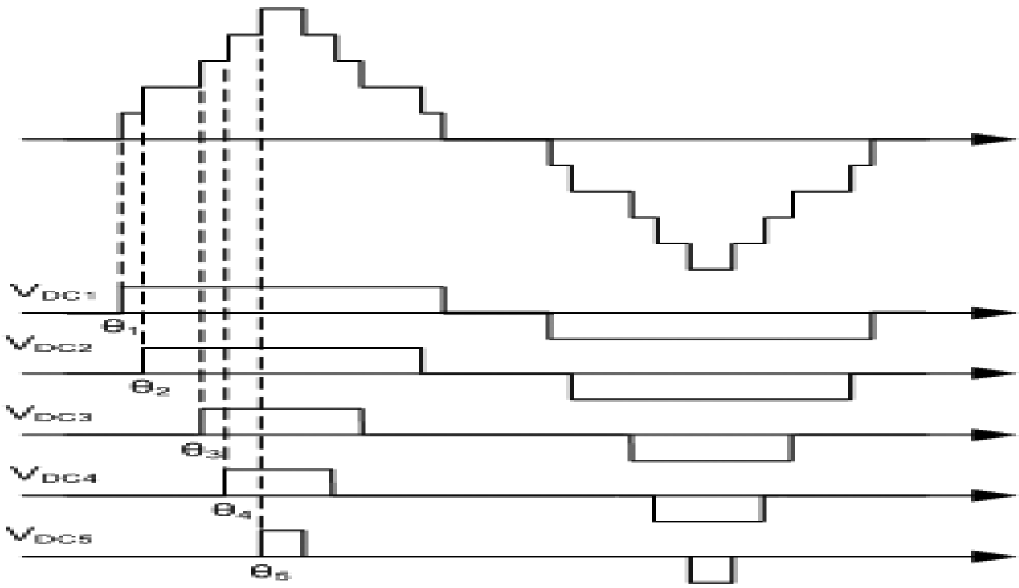

Fig. 3. Output voltage waveform of a single-phase cascaded eleven level inverter

Figure 2 and 3 show the Schematic diagram and Output voltage waveform of a single-phase cascaded h-bridge eleven level inverter. A single-phase 11-level inverter is formed by joining five identical inverter modules in series. All five identical inverter modules having the same magnitude are fed by DC voltage sources. During positive half cycle, the IGBT switches (Q11, Q13) are in the on-state, and the IGBT switches (Q12, Q14) are in the off-state. Likewise, during negative half cycle the IGBT switches (Q11, Q13) are in the off-state, and the IGBT switches (Q12, Q14) are in the on-state and vice versa. The output voltage of the inverter has eleven voltage levels from -5 Vdc. to +5 Vdc. The five different full-bridge inverter ac output levels are connected in series such that the total inverter voltage is the sum of the inverter outputs.

The number of phase output voltage levels m in a cascaded h-bridge inverter is given by

$$m = 2n+1 \qquad (1)$$

where n is the number of separate dc sources.

3. Auto sequencing of Power sources in a cascaded multilevel inverter

A cascaded multilevel inverter using isolated DC sources usually employ step modulation if low frequency scheme is adopted. In the synthesis of the multilevel inverter the power contribution of each level is different. The DC source supplying the lowest voltage level delivers power for more duration than other levels. The DC source that contributes for the highest level has to deliver power only for a short duration of time. Thus when operating over a certain period of time the individual quantity of energy delivered by each of the DC sources will not be equal. Under such circumstances, if the sources are storage batteries or fuel cells then the discharge rates will be different for each battery and there is a definite chance for voltage becoming unequal over time.

The calculations of the switching angles, if assumed with equal source voltages will not hold good if the DC voltage sources become unequal. Thus the expected fundamental voltage magnitude as well as the mitigation of the selected harmonics will be hampered.

In order to avoid this drawback in this work it has been proposed to rotate the DC sources sequentially such that the source that caters to the lowest level period comes next during the next AC output cycle. In this way at the end of every 5 cycles all the sources would have equally burdened. With the equally distributed fall of state of charge of the batteries, the batteries would exhibit the same terminal voltage thus the switching angle estimation would not be affected.

Let V1, V2, V3 V4 and V5 be the terminal voltages of the batteries. Let T1, T2, T3, T4 and T5 be the duration of contribution of each battery in one half cycle. This period of contribution of each battery is decided by the switching angles θ1, θ2, θ3, θ4 and θ5. The topology of the cascaded H bridge inverter keeps the current carried by all the H bridges equal say I amps. Therefore over a cycle of period the power delivered by each H bridge will be

P1 = k1*V1 * I watts

P2 = K2*V2 * I watts

P3 =K3* V3 * I watts

P4 = K4*V4 * I watts

P5 = K5*V5 * I watts……………………………………………………(2) - (6)

Where k1, k2, k3, k4, k5 is the factors by which the power contribution of each DC is different. Therefore since K1>k2>k3>k4>k5 the energy delivered by the DC sources over one cycle period will be (P1*t)>(P2*t)>(P3*t)>(P4*t)>(P5*t),where t is the period of one cycle.

A MATLAB/ SIMULINK platform compares the fall of state of charge of the batteries and its effect on the mitigation of the selected harmonics both with the cases of with and without sequential rotation of the power sources. The experimental verification also validates the proposed method.

4. Particle Swarm Optimization Algorithm

The particle swarm optimization (PSO) calculation has been utilized for evaluating the switching angles θ_1, θ_2, θ_3, θ_4 and θ_5 which will prompt the 5^{th}, 7th, 11th and 13^{th} lower order harmonics minimization in a multilevel inverter. An objective function is used for this reason. This function utilizes the arrangement of five trigonometric transcendental equations containing the switching angles θ_1, θ_2, θ_3, θ_4 and θ_5.

5. Optimized Harmonic Stepped Waveform

The optimized harmonic stepped-waveform technique gives lower THD output and does not require any filter for a Cascaded h-bridge multilevel inverter topology. The Switching devices can withstand the EMI and the switching loss problem by turning them on and off only one time per cycle. Figure. 4 shows an eleven level OHSW output waveform.

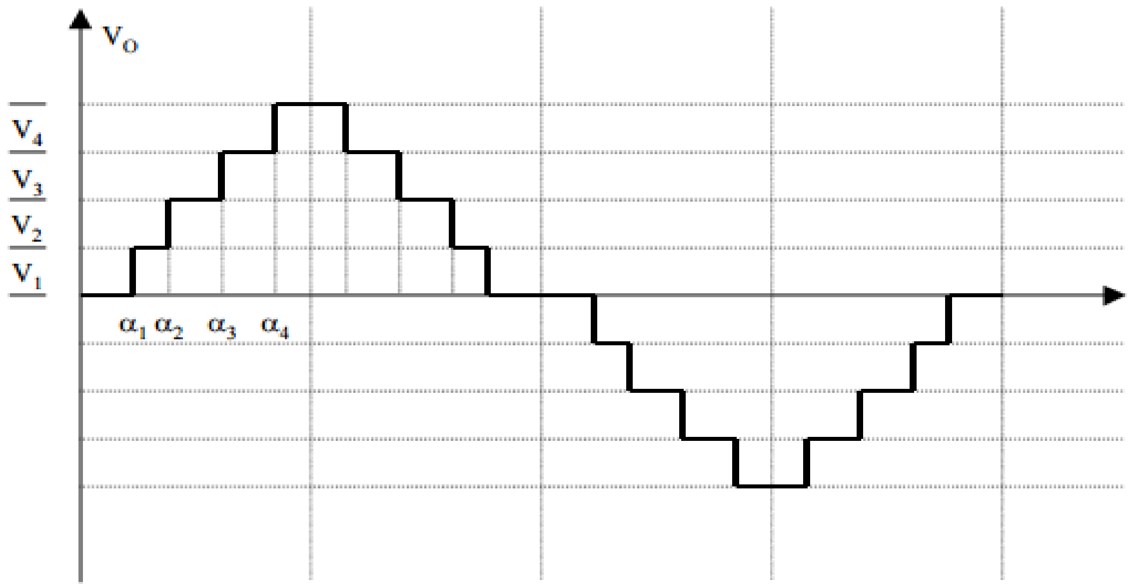

Fig. 4. OHSW output waveform.

V1 to V4 are isolated PV dc sources. Here the optimization technique used for lower order harmonics reduction is optimizing both heights and spaces. The expression of the fundamental amplitude for the unequal amplitude of all dc sources is given by

$$V(\omega t) = \sum_{n=1,3,5}^{\infty} \frac{4V_{pv}}{n\pi} \begin{bmatrix} k_1 \cos(n\alpha_1) + \\ k_2 \cos(n\alpha_2) + \dots \\ +k_m \cos(n\alpha_m) \end{bmatrix} \sin(n\omega t) \quad (1)$$

Where k_i Vpv is the ith dc voltage

Vpv is the nominal dc voltage and the switching angles α_1 to α_m should satisfy the following condition.

$$\alpha_1 \le \alpha_2 \le \alpha_3 \le \dots\dots\dots \le \alpha_m \le \frac{\pi}{2}$$

In the first quarter wave symmetry, the output voltage is zero from the interval zero to α1 and at α1, the output voltage is V1. At α2, the output voltage goes from V1 to (V1+V2) and the process continues upto π /2 where the voltage becomes (V1+V2 + V3+V4+ V5). In the second quarter wave symmetry, output voltage decreases to (V1+V2 + V3+V4) at π - α5. The process will be repeated upto

π -α1 in which the output voltage reaches to zero again to complete a half cycle. In the next half cycle the same process will be repeated. The set of non linear equations to obtain optimal switching angles are given in the equations (2) to (7).

$V1 \cos(\alpha1) + V2 \cos(\alpha2) + \dots\dots + V5 \cos(\alpha5) = M\pi/4$

$V1 \cos(3\alpha1) + V2 \cos(3\alpha2) + \dots\dots + V5 \cos(3\alpha5) = 0$

$V1 \cos(5\alpha1) + V2 \cos(5\alpha2) + \dots\dots + V5 \cos(5\alpha5) = 0$

$V1 \cos(7\alpha1) + V2 \cos(7\alpha2) + \dots\dots + V5 \cos(7\alpha5) = 0$

$V1 \cos(9\alpha1) + V2 \cos(9\alpha2) + \dots\dots + V5 \cos(9\alpha5) = 0$

(2) - (6)

Where M = h1/ $V(1\text{-}5)$

h1 is the fundamental component amplitude

From Eq. (2), control the fundamental amplitude by varying the modulation index. The other nonlinear equations from (3) to (6) are set to be zero and the lowest m-1 odd harmonics can be eliminated.

6. Simulation results

The performance of the OHSW PWM based cascaded H-bridge eleven level inverter with isolated dc sources is determined through MATLAB/SIMULINK software. The elements and the parameters considered for simulation are presented in Table 1.

Table 1

Parameters of the Cascaded H-Bridge Inverter

Parameters	Values
No. of H-Bridge levels	5
No. of Switches	20
DC source voltage for individual H- bridge	17.5V
Fundamental frequency	50Hz
Load resistor	100 Ohm
Load Inductor	40mH

The simulation model of cascaded h-bridge eleven level inverter topology using OHSW PWM is shown in fig.5. The main power circuit consists of five H-bridges whose dc voltage is 17.5 V and PWM block contain parameters as pulse width period, phase delay and amplitude. Thus the eleven level stepped output voltages are obtained and the harmonics are reduced. Therefore the inverter efficiency is increased.

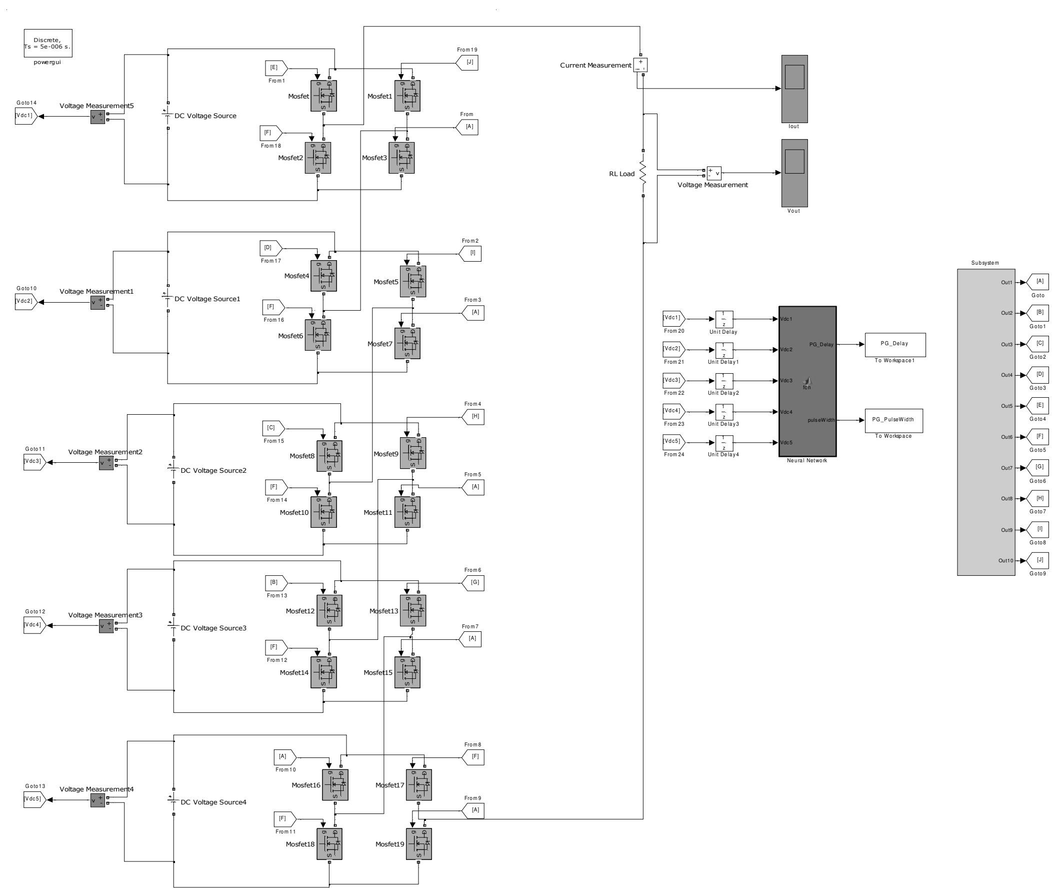

Fig. 5. Simulation model of cascaded h-bridge eleven level inverter topology

The results are taken for modulation index M = 0.71 in MATLAB software. The Output voltage and current waveform of Cascaded h-bridge eleven level inverter are shown in fig. 6 & 7.

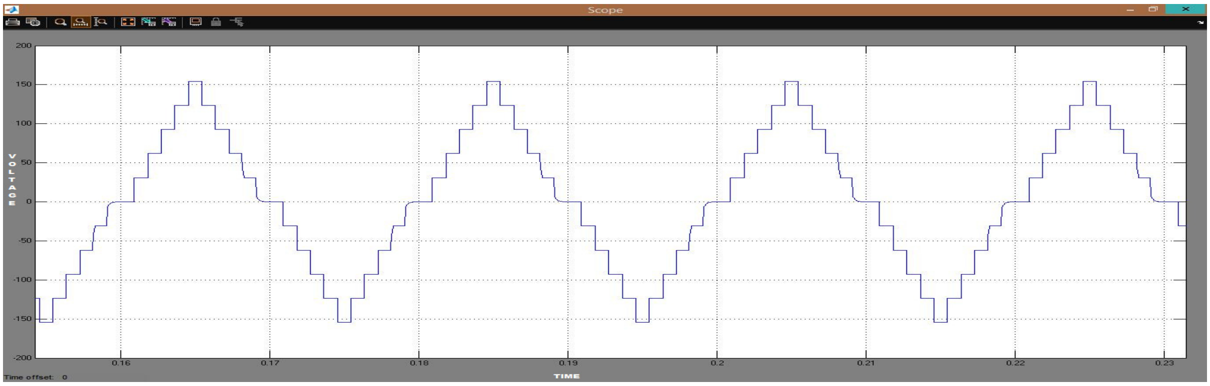

Fig. 6. Output voltage waveform of Cascaded h-bridge eleven level inverter

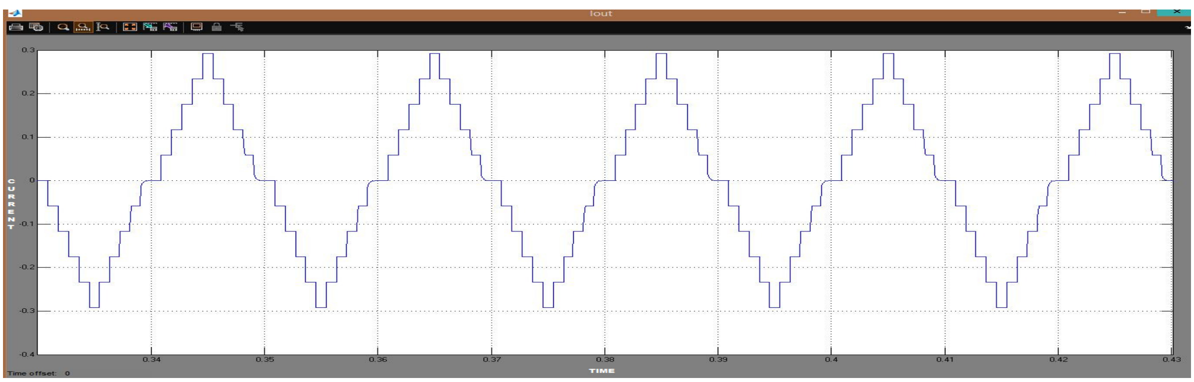

Fig. 7. Output current waveform of Cascaded h-bridge eleven level inverter

THD is the summation of all harmonic components of the current or voltage waveform. The number of harmonics to be eliminated is equal to the number of switching angles - 1 are obtained.

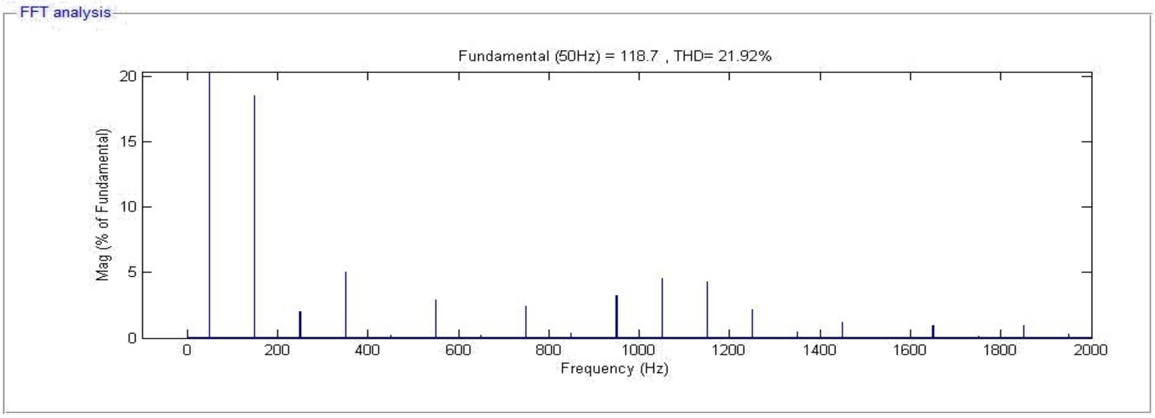

Fig. 8. Harmonic spectrum of the inverter output voltage

From the harmonic spectrum of the inverter output current shown in fig.8, lower order harmonics such as 5th, 7th, 11th, and 13th magnitudes are very small. With reference to table 2, a comparison of THD of the output voltage is done for the proposed algorithm (PSO) and existing Genetic algorithm.

Table 2

Comparison of THD of the output voltage

Modulation Index M	Switching angles in terms of radians					THD(%)	
	θ_1	θ_2	θ_3	θ_4	θ_5	PSO	GA
0.51	0.79	0.89	1.06	1.26	1.34	26.98	25.74
0.63	0.60	0.66	0.87	1.03	1.12	24.02	25.86
0.67	0.44	0.56	0.75	0.98	1.08	23.24	24.12
0.71	0.25	0.42	0.66	0.94	1.02	21.92	23.56

7. Conclusion

In this paper, minimization of lower order harmonics utilizing OHSW PWM methodology is explored. With the equally distributed output power, the power balance is kept up among the different sources, thus the switching angle estimation would not be influenced. Simulation results also represent the execution and viability of the proposed circuit for produces a high-quality output voltage waveform and harmonic components of output voltage and current are low when compared to the existing algorithm.

References

[1] Carrasco JM, Franquelo LG, Bialasiewicz JT, Galvan E, PortilloGuisado RC, Prats MAM, Leon JI, Moreno-Alfonso N. Power-electronic systems for the grid integration of renewable energy sources: A survey. *IEEE Trans. Ind. Electron. 2006;* 53;1002–1016.

[2] Agelidis VG, Baker DM, Lawrance WB, Nayar CV. A multilevel PWM inverter topology for photovoltaic applications. *Proc.IEEE ISIE*, Guimarães, Portugal. 1997; 589–594.

[3] Kouro S, Rebolledo J, Rodriguez J. Reduced switching-frequency modulation algorithm for high-power multilevel inverters. *IEEE Trans.Ind. Electron.*2007; 54; 2894–2901.

[4] Park SJ, Kang FS, Lee MH, Kim CU. A new single-phase five level PWM inverter employing a deadbeat control scheme. *IEEE Trans.Power Electron.*2003; 18; 831–843.

[5] Tolbert LM, Habetler TG. Novel multilevel inverter carrier-based PWM method. *IEEE Trans. Ind. Appl.*1999; 35; 1098–1107.

[6] Calais M, Borle LJ, Agelidis VG. Analysis of multicarrier PWM methods for a single-phasefive-level inverter. *Proc. 32nd Annu. IEEEPESC*.2001; 3; 1173– 1178.

[7] Choi NS, Cho JG, ChoGH. A general circuit topology of multilevel inverter. *Proc. 22nd Annu. IEEE PESC*. 1991; 96–103.

[8] Carrara G, Gardella S, Marchesoni M, Salutari R, Sciutto G. A new multilevel PWM method: A theoretical analysis. *IEEE Trans. Power Electron.*1992; 7 ; 497–505.

[9] Nabae A, Akagi H. A new neutral-point clamped PWM inverter. *IEEE Trans. Ind. Appl.*1981; IA-17; 518–523.

[10] Pou J, Pindado R, Boroyevich D. Voltage-balance limits in four level diode-clamped converters with passive front ends. *IEEE Trans. Ind.Electron.*2005; 52; 190–196.

[11] Alepuz S, Busquets-Monge S, Bordonau J, Gago J, GonzalezD, Balcells J. Interfacing renewable energy sources to the utility grid using a three-level inverter. *IEEE Trans. Ind. Elec tron.*2006; 53; 1504–1511.

[12] Meynard T, Foch H. Multi-level choppers for high voltage applications. *Eur. Power Elec tron. 1992;* 2; 45–50.

[13] Kang DW, B.-K. Lee, J.-H. Jeon, T.-J. Kim, and D.-S. Hyun, "A symmetric carrier technique of CRPWM for voltage balance method of flying capacitor multilevel inverter," *IEEE Trans. Ind. Elec tron.*, vol. 52, no. 3, pp. 879–888, Jun. 2005.

[14] Lin BR, Huang CH. Implementation of a three-phase capacitor clamped active power filter under unbalanced condition. *IEEE Trans. Ind. Electron.* 2006 ; 53 ; 1621–1630.

[15] Marchesoni M, Mazzucchelli M, Tenconi S. A non-conventional power converter for plasma stabilization. *Proc. IEEE Power Electron.Spec. Conf.* 1988 ; 122–129.

[16] Rodriguez J, Hammond P, Pontt J, Musalem R, Lezana P, Escobar M. Operation of a medium-voltage drive under faulty conditions. *IEEE Trans. Ind. Electron.*52 ; 1080– 1085.

[17] Kou X, Corzine K, Wielebski M. Overdistortion operation of cascaded multilevel inverters. *IEEE Trans. Ind. Appl.* 2006; 42; 817–824.

[18] Rodriguez J, Lai JS, Peng FZ. Multicarrier PWM strategies for multilevel inverters. *IEEE Trans. Ind. Electron.*2002; 49; 724–738.

[19] Filho F, Cao Y, Tolbert LM. 11-level cascaded H-bridge grid-tied inverter interface with solar panels. *IEEE Proc. Applied Power Electronics Conference and Exposition (APEC)*. 2010; 968-972.

[20] Townsend CD, Summers TJ, Betz RE. Control and modulation scheme for a cascaded H-bridge multi-level converter in large scale photovoltaic systems. *IEEE Proc. Energy Conversion Congress and Exposition (ECCE)*. 2012; 3707 – 3714.

[21] Albert Alexander S, Manigandan Thathan. Optimal Harmonic Stepped Waveform Technique for Solar Fed Cascaded Multilevel Inverter. Journal of Electr Eng Technology. 2015; 10; 742-751.

[22] Firouzkouhi. Control of Cascaded H-bridge Multilevel inverter based on optimum regulation of switching angles, with FPGA implementation. European journal of electrical

and computer engineering. 2019;3.

[23] Selvaperumal.S, Sivagama Sundari M S, A Comparative Analysis of Multicarrier Modulation Strategies for Cascaded H-Bridge Multilevel Inverter. Journal of Computational nanoscience. 2017; 14; 6020-6029.