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FPGA BASED HARDWARE IMPLEMENTATION OF WTHD MINIMISATION IN ASYMMETRIC MULTILEVEL INVERTER USING BIOGEOGRAPHICAL BASED OPTIMISATION

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Abstract: *Harmonic Elimination and THD Minimisation in asymmetric cascaded multilevel inverter involves complex nonlinear non convex trigonometric transcendental equations which has several solutions.Among the various topologies of cascaded multilevel inverter asymmetric cascaded multilevel inverter has the advantage of reduced switch count when compared to traditional symmetric multilevel inverter topology. In this paper FPGA based hardware implementation is carried for a 13 level inverter by using offline computation of switching angle with weighted total harmonic distortion (WTHD) as the objective function. WTHD optimisation offers the blend of eliminating the specific lower order harmonics as in SHE-PWM and minimisation of THD as in OMTHD. The simulation and experimental results were presented for 7 level symmetric and 13 level asymmetric inverter. The experimental waveforms were analysed for THD and lower order harmonics using fluke power analyser and comparison of WTHD with SHE-PWM and OMTHD are presented .The results indicates that in a 13 level inverter the WTHD based optimisation yields reduced THD of 5.35% in simulation and 5.9% experimentally.It also eliminates all the specified 5^{th} ,7^{th} ,11^{th} ,13^{th} and 17^{th} lower order harmonics.*

Keywords: *WTHD,BBO,SHE- PWM,OMTHD.*

1. Introduction

Multilevel voltage source inverters are used for medium and high power applications and have drawn incredible interest in power sector and distributed energy interface [1], [2]. The various topologies of multilevel inverter are diode clamped, capacitor clamped and cascaded topology [3]. The series connected cascaded H-bridge converters is preferred due to the modularity and simplicity of control. Multilevel converters has emerged popularly and has colossal development in fields such as static compensators, AC drives[5], HVDC Transmission[6] , fuel cell [7], photo voltaics [8], topologies and modulation and control techniques [4] .

The control, power quality and performance of the cascaded symmetric and asymmetric H bridge multilevel inverters can be improved by using High frequency carrier based PWM techniques and fundamental frequency methods. High frequency carrier based PWM technique like phase disposition, phase opposition disposition, phase shifted PWM [9] were not able to eliminate the lower order harmonics and also causes high switching losses.Thus the fundamental frequency switching techniques such as selective harmonics elimination (SHE-PWM), optimized harmonic-stepped waveform(OHSW) and optimal minimization of THD (OMTHD) are applied for harmonic optimisation in multilevel inverters [4].

In Selective Harmonic Elimination SHE-PWM switching angles are pre determined offline so as to eliminate the specific lower order harmonics and maintain the required fundamental voltage [10-12]. The number of lower order harmonics eliminated depends on the number of degrees of freedom .A thirteen level inverter has six switching angles as degrees of freedom and thus eliminates 5^{th}, 7^{th} 9^{th} ,11^{th} and 13^{th} order harmonics . OMTHD is a proficient method, by which the switching angles are determined so as to minimize the waveform THD while the desired fundamental component is retained. The THD optimisation can also be directly applied on the line THD [13].

Another technique named as selective harmonic mitigation technique (SHM) [14-15] limits the harmonics within the IEC standard grid code but it does not provide complete elimination of the specified lower order harmonics. Multilevel selective harmonic elimination (MSHE) [16] switches more than once in a level and eliminate more harmonics from the harmonic spectrum and offer better harmonic performance . In distributed energy sources with increase in number of solar array, the number of levels increases and MSHE formulation becomes more

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complex. Thus in this paper fundamental frequency with only one switching per level is considered .

The main difficulty in SHE-PWM and OMTHD method is to solve the non-linear transcendental equations which has multiple local minimal solutions [17]. Conventionally newton raphson method was used but it has the divergence problem and it also requires good starting point, closer to the exact solution patterns. The approach based on mathematical resultant theory to calculate the optimum switching angles, involves very high degree of polynomials [18-19] .As number of levels increases, deriving and solving high degree polynomial is very complex.

Modern meta-heuristic algorithms like Genetic algorithm [20] , simulated annealing [21], PSO [22] , bacterial foraging algorithm (BFA), homotopy [23], modified species- based particle swarm optimization [24] were employed in literature for harmonic optimisation problems in multilevel inverter . The PSO based algorithm is presented for SHE-PWM technique in the literature [22]. BBO has not been applied in the previous literatures for harmonic elimination and WTHD optimisation.

In PSO, solution varies indirectly depending on the velocity. In newly introduced optimisation algorithm BBO [25] the solution changes directly based upon the immigration rate and emigration rate; the best populations are directly obtained by the use of migration .The results obtained by BBO indicates faster convergence rate and produces global optimum when compared to PSO [26-28].

BBO technique for weighted total harmonic distortion (WTHD) minimisation is presented in this paper for symmetric and asymmetric multilevel inverter.Simulation and experimental results for a seven level symmetric and thirteen level asymmetric cascaded multilevel inverter are presented to show the validity of the proposed technique.

2. Hybrid cascaded multilevel inverter

The asymmetrical multilevel inverters have received increasing attention as it synthesizes voltage waveforms with reduced harmonic content, with few H bridge cells. The hybrid asymmetric inverter is classified as binary and trinary multilevel inverter. The binary multilevel inverter is shown in Figure 1. The voltage sources of the consecutive bridges are in multiples of two. The number of levels produced in binary hybrid multilevel inverter is given by $2^{(n+1)}-1$. If there are three voltage sources, then the maximum number of levels produced in the output is fifteen ($2^{(3+1)}-1$). Thus three voltage sources in the ratio of 1:2:4 and 12 switches are required to produce maximum of thirteen levels in binary hybrid multilevel inverter. In a cascaded multilevel inverter with equal DC sources 24 switches and six voltages sources are required to produce the same 13 level.

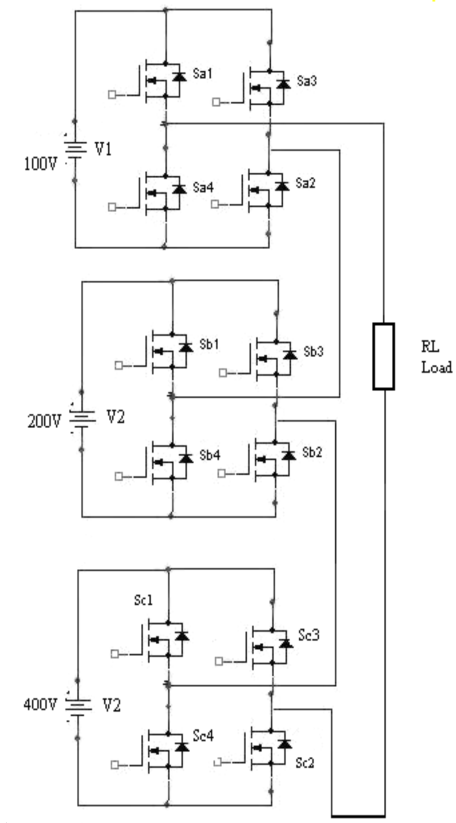

Figure 1. Topology of a thirteen level single phase asymmetric cascaded inverter

In the same hardware with three H bridges, traditional cascaded multilevel inverter has DC voltage ratio 1:1:1 and produces seven level output whereas asymmetric topology with voltage ratio 1:2:4 produces thirteen level output.

3. Problem formulation

The Fourier series expansion for a thirteen level cascaded multilevel inverter is shown in (1):

$$V_{out}(\omega t) = \sum_{n=1,3,5}^{\alpha} \frac{4Vdc}{n\pi} * [K_1 \cos(n\theta_1) + K_2 \cos(n\theta_2) + K_3 \cos(n\theta_3) + K_4 \cos(n\theta_4) + K_5 \cos(n\theta_5) + K_6 \cos(n\theta_6)] \sin(n\omega t) \quad (1)$$

Here equal DC sources are considered and thus $K1=K_2=K_3=K_4=K_5=1$, Vdc is the nominal dc voltage, and the switching angle limit is from

$$0 \leq \theta_1 \leq \theta_2 \leq . . . \leq \theta_6 \leq \pi/2$$

The traditional evaluation factor THD is represented by equation (2).The formula shows that equal weights are assigned to all harmonics irrespective of lower and higher order.

$$\mathrm{THD} = \frac{\sqrt{\sum_{i=2}^{50}(V_h)}}{V_1} \quad (2)$$

In SHE-PWM the series of switching angles $\theta_1 - \theta_6$ are chosen to suppress the specified lower order harmonics and to maintain the desired amplitude of the fundamental value. In a three phase system, the triplen harmonics are automatically eliminated and thus they are not considered. The disadvantage of this method is higher order harmonics like b19, b23, b25, b29 are not eliminated. The SHE-PWM function is given by equation (3).The cost function of SHE-PWM for various angles θ1 and θ2 is shown in Figure 2. Although thirteen level inverter is used in this paper, to represent in three dimensional view, 5 level inverter with 2 angles is considered.

$$SHE\ PWM = 100 * \ b1 - Vref \ + 10 * (b5 + b7 + b11 + b13 + b17)$$

$$bn = \frac{4Vdc}{n\pi} \sum_{i=1}^{\alpha} \cos n\theta_i \qquad (3)$$

Where b_n denotes the n^{th} order harmonics and n=1,5,7,11,13,17.

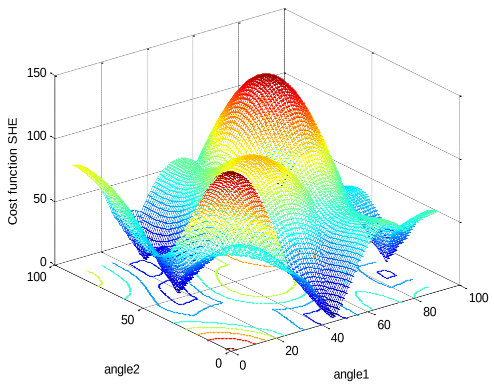

Figure 2. Cost function for various angles

In WTHD, the harmonic voltages are represented as the ratio of harmonic order. In equation (4) the harmonics are divided by its order and thus multiplication factor or weights vary for individual harmonics .WTHD emphasis on more weights for lower order harmonics and less weights for higher order harmonics and thus the THD and lower order harmonics both are minimized .WTHD is represented using the formula (4),

$$WTHD = \frac{\sqrt{\sum_{i=2}^{50} (\frac{V_i}{i})^2}}{V_1} \qquad (4)$$

Where,
V_1 is the fundamental component,
i is the order of harmonics,

4. Biogeography Based Optimization

Biogeography Based Optimization (BBO) mimics the natural motivation of the distribution of animals and plants. BBO algorithm primarily deals with the migration of species from one island to another [25]. The term island is referred to as habitat. Habitat suitability index (HSI) indicates the best space or region for the species to survive. The HSI rate, immigration rate and emigration rate that occurs between neighbour hood solutions decides the next generation. The emigration rate and immigration rate determines the best region for movement. The quality of solutions is increased by mutation . During the process the results of poor solution migrates towards good ones.

5. BBO Algorithm for 13 Level Inverter

Step 1) Initialise the number of switching angles to be optimised as Suitability Index Variable (SIV) and SIV=6 for a thirteen level inverter. Initialize the various parameters of BBO like probability of habitat modification, probability of mutation, mutation rate, immigration rate, emigration rate, step size, elitism parameter and number of iteration.

Step 2) The habitat is generated in random and represented by [θ1 θ2 θ3 θ4 θ5 θ6]. The boundary constraint for the switching angle is $0 < \theta 1 < 90^o$ as it has to obey quarter wave symmetry.

Step 3) Calculate the HSI for each habitat set for given emigration rate μ, immigration rate λ. HSI or fitness function is the minimum WTHD of the multilevel inverter and is given by equation (5)

$$\mathrm{WTHD} = \frac{\sqrt{\sum_{i=2}^{50} (\frac{V_i}{i})^2}}{V_1} \qquad (5)$$

The switching angles are generated and fitness values are calculated. The SIV for HSI is represented as

$$H = SIV = [\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6]$$

Step 4) Based on the WTHD value best solution or elite habitats are identified.

Step 5) Probabilistically perform migration operation on the SIV of every non-elite habitats, which is selected for migration.

Step 6) The procedure to select an SIV for migration operation is to choose the lower and upper value of immigration rate (λ_{lower} and λ_{upper}). Access the value of λ and μ for each habitat set. Select the SIV to be chosen for recently generated habitat after migration.

Step 7) Normalize the immigration rate using the equation (6).

$$\lambda_{Scale} = \lambda_{Lower} + \ \lambda_{Upper} - \lambda_{Lower} \ * (\lambda(K) - \lambda_{Min}) / (\lambda_{Max} - \lambda_{Min}) \qquad (6)$$

Step 8) Mutation operation is performed on the non-elite habitat. In mutation operation, re-establish the selected habitat by random habitat set.

Step 9) Proceed with the step (3) for the next iteration and the looping continues for predefined number of iterations.

6. Simulation result

To validate the WTHD based optimisation and to compare its performance with OMTHD and SHE-PWM simulation is carried out in MATLAB.The mfile programming is done to find out optimised switching angles for a seven and thirteen level inverter using (i)OMTHD and SHE-PWM (ii)WTHD.

6.1 OMTHD and SHE-PWM approach

6.1.1.Seven Level Inverter

The optimized switching angles obtained by BBO for OMTHD and SHE-PWM for modulation index m=1 is shown in Table 1. OMTHD equally minimises both the lower and higher order harmonics and thus it has reduced phase THD of 11.28% but has considerable specified lower order harmonics of 0.167.

In SHE-PWM approach phase THD is 12.63 % and the values of eliminated lower order harmonics is 0.031.Thus SHE-PWM significantly eliminates specified lower order harmonics whereas higher order harmonics are more pronounced. SHE-PWM offers 81.43% reduction of selected harmonics but 10% increased THD when compared to OMTHD.

6.1.2.Thirteen Level Inverter

The optimized switching angles for 13-level inverter obtained by BBO for OMTHD and SHE-PWM with modulation index m=1 is given in Table 2 and Table 3 respectively. The BBO results for two different runs with change in number of iterations are taken to compare the performance. Table 2 shows that for lowest selective harmonic values the phase THD is very high. Table 3 shows that when selective harmonics h5, h7, h11, h13, h17 are completely eliminated to lowest value of 0.20, the THD increases to 10.6%.

6.2 WTHD Based approach

Thus a technique termed as WTHD minimisation which intermingles the feature of both the techniques is presented. BBO based optimisation for seven and thirteen level inverter is performed with minimisation of WTHD as the objective function .The WTHD optimised switching angle for different modulation index is given in Table 4. and the plot is shown in Figure 3. The plot of lower order harmonics and consecutive higher order harmonics is shown in Figure 4 and Figure 5. This method overweighs the previous method as both THD and SHE-PWM function is reduced. For a seven level inverter the WTHD minimization approach is applied and the switching angle and comparison results are given in the Table 5. In a seven level inverter the optimised value of WTHD is 0.78% and lower order harmonics is 0.089. This result shows that WTHD offers 9% reduction in THD when compared to SHE-PWM and 40% reduction in eliminated harmonics when compared to OMTHD.

For a thirteen level inverter the optimised value of WTHD and comparison results are shown in Table 6 .It indicates a value of 0.31% as WTHD and lower order harmonics value as 0.24. The harmonics eliminated using all the three techniques are given in Table 7.This shows that WTHD is superior to OMTHD, as the technique yields THD of 5.6% similar to OMTHD and also results in 48% reduction in selected harmonics when compared to OMTHD.

7. Experimental Results

The prototype of seven and thirteen level inverter is implemented in hardware using Xilinx spartan 3A X3CS50AN FPGA controller and MOSFET IRF340. FFT analysis and THD measurement is performed using fluke power logger Fluke 1735.

7.1.Seven Level Inverter

The experimental output phase voltage waveform for seven level cascaded asymmetric inverter for WTHD technique with m=1 is shown in Figure 6(a) . In OMTHD technique, the THD is reduced to 11.8% but specified lower order harmonics h5, h7 shows higher values and are not eliminated as shown in Figure 6(b).

In WTHD technique the phase THD has increased to 12.6% experimentally and specified h5 , h7 harmonics are entirely eliminated and it is shown in Figure 6(c).

7.2.Thirteen Level Inverter

The oscillogram of phase voltage of 13 level waveform for WTHD based approach is shown in Figure 7(a). The FFT spectrum of OMTHD approach shown in Figure 7(b), indicates that values of h11 and h17 are more pronounced but THD value is reduced to 5.9%.

In WTHD approach the value of phase THD is found to be 6.2% experimentally and is shown in Figure 7(c) . Also the FFT analysis performed using fluke power logger shows that all the specified lower order harmonics are eliminated and 21^{st} and 29^{th} harmonics only exists .

The CDF plot for the convergence of BBO and PSO for the different runs is shown in Figure 8 . It shows that BBO has faster convergence than PSO.

Table 1. Optimum switching angles, phase THD and lower order harmonics for 7-level OMTHD and SHE-PWM

Technique	θ1°	θ2°	θ3°	phase thd %	line thd %	h5	h7	SHE
OMTHD	9.49	27.63	50.68	11.28	10.52	0.090	0.077	0.167
SHE	11.02	30.35	58.96	12.63	7.71	0.028	0.003	0.031

Table 2. Optimum switching angles, phase THD and harmonics for OMTHD approach in 13 level inverter

θ1°	θ2°	θ3°	θ4°	θ5°	θ6°	THD ph (%)	line THD (%)	v1	h5	h7	h11	h13	h17	SHE
5.73	19.21	26.35	37.79	49.25	63.83	6.93	5.49	6.0	0.134	0.001	0.052	0.005	0.111	0.31
5.73	12.93	24.54	34.44	46.60	57.82	5.56	5.68	6.2	0.127	0.149	0.020	0.051	0.065	0.41

Table 3. Optimum switching angles, phase THD and harmonics for SHE- PWM approach in 13 level inverter

θ1°	θ2°	θ3°	θ4°	θ5°	θ6°	THD ph (%)	line THD (%)	v1	h5	h7	h11	h13	h17	SHE
12.9	13.51	24.48	34.45	57.40	60.60	10.60	5.65	6	0.030	0.069	0.011	0.008	0.087	0.20
5.73	18.88	24.20	39.15	50.64	63.26	7.09	5.61	6	0.062	0.055	0.024	0.004	0.155	0.30

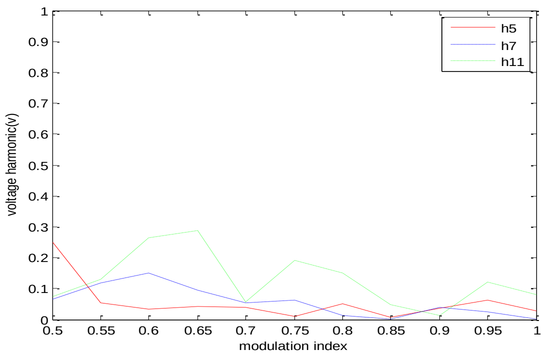

Figure 3. Modulation index, M vs lower order harmonics for 7- level symmetric multilevel inverter in WTHD approach

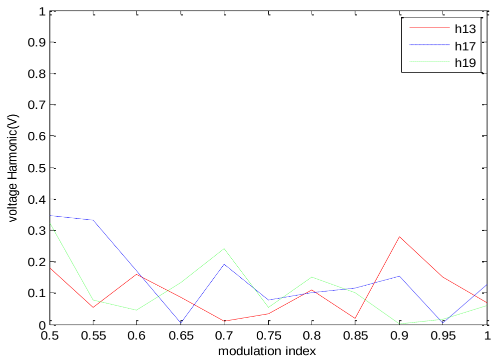

Figure 4. Modulation index, M vs higher order harmonics for 7- level symmetric multilevel inverter in WTHD approach

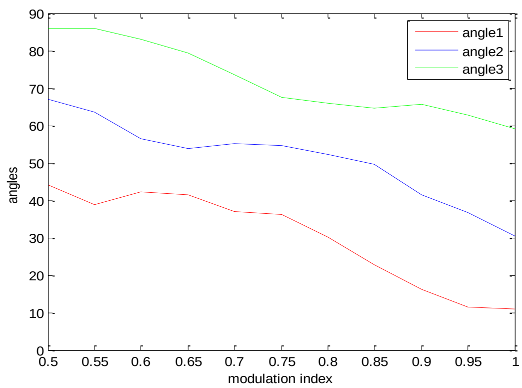

Figure 5. Modulation index, M versus Switching angles for 7- level symmetric multilevel inverter in WTHD approach

Table 4.WTHD optimisation for different modulation index in 7-level inverter

M	θ 1°	θ 2°	θ 3°	h1	h5	h7	h11	h13	WTHD (%)	THD ph (%)	SHE	Line THD (%)
1.00	9.91	28.51	54.12	3.00	0.03	0.07	0.02	0.13	0.78	11.42	0.09	9.66
0.95	11.52	36.79	62.79	2.85	0.06	0.02	0.12	0.15	1.36	15.27	0.36	8.49
0.90	16.10	41.48	65.62	2.70	0.04	0.04	0.01	0.28	1.86	19.40	0.37	11.61
0.85	22.69	49.60	64.63	2.55	0.01	0.00	0.05	0.02	1.35	28.40	0.08	8.41
0.80	30.04	52.29	65.84	2.40	0.05	0.01	0.15	0.11	1.64	36.16	0.33	10.19
0.75	36.06	54.59	67.40	2.26	0.01	0.06	0.19	0.03	1.59	43.73	0.30	9.92
0.70	36.92	55.26	73.47	2.11	0.04	0.05	0.06	0.01	1.97	44.85	0.16	12.29
0.65	41.41	53.71	79.29	1.95	0.04	0.09	0.29	0.09	2.04	48.75	0.51	12.71
0.60	42.17	56.42	83.07	1.80	0.03	0.15	0.27	0.16	2.55	50.26	0.61	15.87
0.55	38.82	63.54	85.94	1.65	0.05	0.12	0.13	0.05	2.56	52.95	0.35	15.99
0.50	44.08	67.01	85.94	1.50	0.25	0.07	0.07	0.18	3.30	57.33	0.57	20.54

Table 5. Comparison of WTHD ,OMTHD and SHE- PWM harmonics for seven level inverter

	θ1°	θ 2°	θ 3°	phase THD(%)	SHE	WTHD (%)	h5	h7	Experimental THD(%)
OMTHD	9.487	27.632	50.677	11.285	0.151	1.0208	0.090	0.077	11.6
SHE	11.02	30.35	58.96	12.63	0.03	1.1971	0.028	0.003	12.6
WTHD	9.907	28.506	54.115	11.424	0.089	0.780	0.034	0.065	11.8

Table 6. Comparison of WTHD ,OMTHD and SHE-PWM harmonics for thirteen level inverter

M	θ1°	θ 2°	θ 3°	θ4°	θ 5°	θ 6°	Phase THD (%)	Line THD (%)	WTHD (%)	SHE	Exp -THD (%)
OMTHD	5.73	12.93	24.54	34.44	46.60	57.82	5.56	5.68	0.571	0.41	5.9
SHE-PWM	12.93	13.51	24.48	34.45	57.40	60.60	10.60	5.65	1`.296	0.20	6.2
WTHD	5.73	15.48	24.37	34.25	47.68	66.96	5.6	5.35	0.31	0.24	6.2

Table 7. Lower order harmonic values for 13 level inverter

Technique	h5	h7	h11	h13	h17
OMTHD	0.127	0.149	0.020	0.051	0.065
SHE-PWM	0.030	0.069	0.011	0.008	0.087
WTHD	0.010	0.084	0.045	0.088	0.008

Figure 6. phase voltage waveform by WTHD approach .

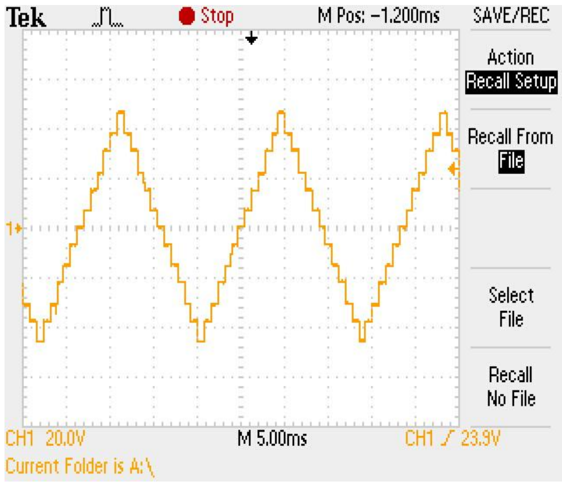

Figure 7. phase voltage waveform by WTHD approach

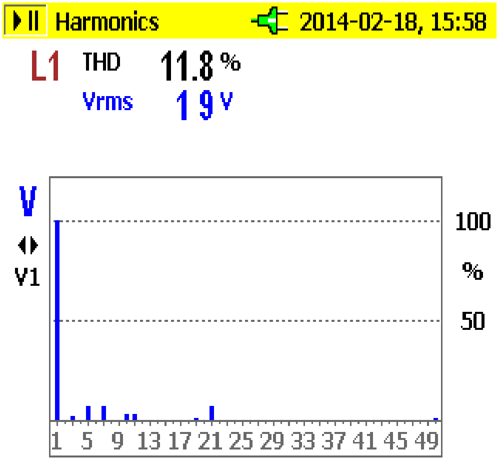

Figure 6(a). FFT analysis of phase voltage by OMTHD approach.

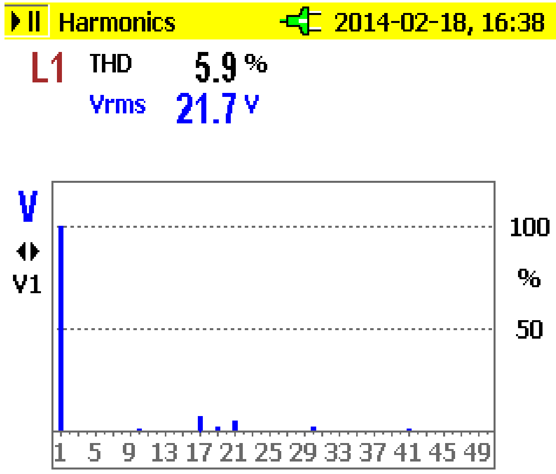

Figure 7(a) FFT analysis of phase voltage by OMTHD approach

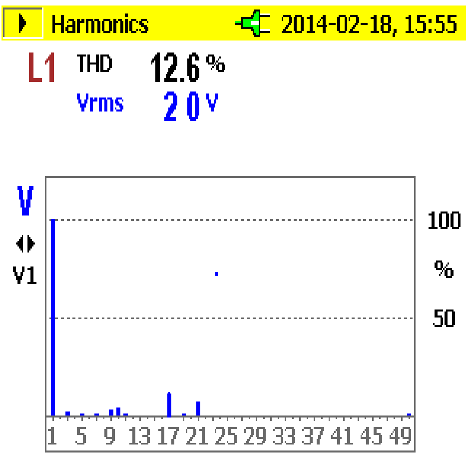

Figure 6(b). FFT analysis of phase voltage by WTHD approach.

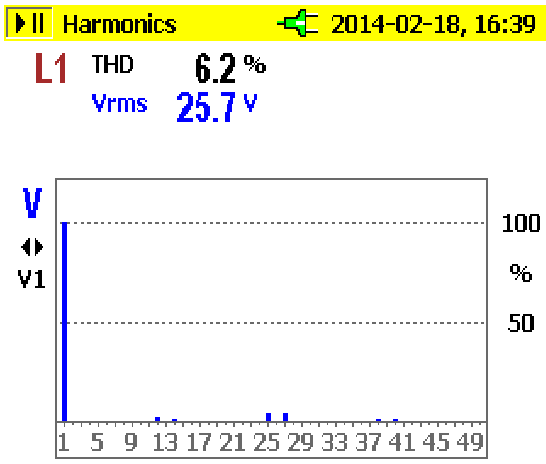

Figure 7(b). FFT analysis of phase voltage by WTHD approach

Figure 6. Experimental results of 7- level symmetric inverter

Figure 7. Experimental results of 13- level asymmetric inverter

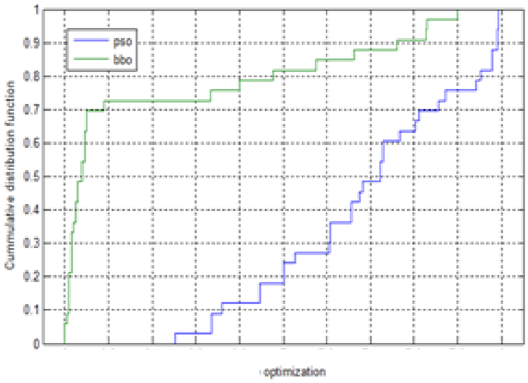

Figure 8. CDF plot for comparison between PSO and BBO

8. Conclusion

In this paper a novel BBO technique is employed to solve WTHD optimisation problem in H bridge cascaded 7-level symmetric and 13-level asymmetric inverter . simulation results reveals that BBO based optimization has faster convergence and yields global minimum when compared to PSO.Simulation ,experimental results and FFT analysis are presented for 7 level symmetric and 13 level asymmetric inverter to confirm the accuracy of suggested WTHD method.Comparison between OMTHD, WTHD and SHE-PWM approach is performed both in simulation and experiment. The OMTHD approach has reduced THD of 5.9% which is 4% lower than WTHD, but h11 and h17 harmonics are not eliminated.The experimental results shows that WTHD based optimization is superior as it gives THD of 6.2% which is only 4% higher than OMTHD but eliminates all the specified harmonics . Thus WTHD based optimization is an efficient approach which offers combined advantage of reducing both THD and lower order harmonics .

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