Selective Harmonics Mitigation Modulation Scheme Applied to CHB and NPC Multilevel Inverters

R. Umamageswari[1], C.R.Balamurugan[2], T.A. Ragavendiran[3]
Research scholar, Department of Electrical and Electronics Engineering, Anna University, Chennai.
Professor, Department of Electrical and Electronics Engineering, Karpagam College of engineering, Coimbatore.
Research Supervisor, Department of Electrical and Electronics Engineering, Anna University, Chennai.

***Abstract*—Energy demand from renewable energy sources is increasing every day. Therefore, there is necessity to integrate large scale solar PV based systems in the grid in compliance with the specific grid codes. The inverter is the most important component of the Solar PV based system. Multilevel inverter (MLI) has various rewards such as less EMI issues, voltage stress and switching losses, it is a best choice for industrial bid. In tradition inverters, Harmonics can be eliminated by using large size of filters due to the lower order harmonics. This leads to growth the overall size, volume and cost of an inverter. Nonetheless in MLI, the implementation of selective harmonic elimination (SHE) techniques eliminates lower order harmonics. The multilevel inverters (MLI) are capable of generating high quality waveforms of voltage (stepped in nature) with reduced distortion in harmonics (less THD), operates at less switching frequency and impress low current and voltage stress on the switching devices. MLI is preferred for large scale PV integration over conventional two-level inverter. Also for large power and high voltage application, the rating of the devices and switching frequency are limited. In MLI, Cascade H-Bridge (CHB) and Neutral Point clamped (NPC) is a best choice for PV and drives applications. In medium and high power applications, usage of high switching frequencies is not recommended because the thermal losses due to switching loss could damage the switching devices. In this context, modulation techniques based on pre-computed pulse width modulation (PWM) switching patterns can be very useful because the generated harmonic content can be previously known and optimized as much as possible. In this paper a 3 level CHB and NPC inverters, modulated with SHE-PWM is proposed for PV application.**

Keywords—Solar PV, Cascade H-Bridge ,Neutral point clamped inverter, selective harmonics elimination , multi-level inverter, pulse width modulation, transcendental equations, Modulation index

I. INTRODUCTION

Grid-connected solar photo-voltaic (PV) system is growing at a very rapid amongst the available renewable energy sources. In fact, it has increased at an average growth of 58% per year in the last half decade [1]. The most commonly used Power electronics interface of PV system with grid consist of a diode rectifier, boost converter, MPPT algorithm and a three-phase three-leg two-level voltage source inverter (2L-VSC) connected via a mains transformer with a delta-star connection [2]. Normally 2L-VSC are operated at high switching frequency (several kHz) with the modulations techniques namely space vector pulse width modulation (SVPWM) and sinusoidal pulse width modulation (SPWM) and [3]–[5]. An output filter is also required in order to comply with the grid codes, to meet the required power quality. This degrades the efficiency of the system and made system costly and bulky. The emerging Topologies such as multilevel inverters (MLI) are capable of generating high quality waveforms of voltage (stepped in nature) with reduced distortion in harmonics (less THD), at low switching frequency, using the IGBTs/MOSFETs devices having low current and voltage ratings and generation of low dv/dt on switches [6-7]. As per IEEE 591 standard the THD of the injected current should not exceed 5%. To obtain such a fine quality output voltage, the inverter switching frequency is kept at high value[8], [9]. However, high switching frequency causes higher switching losses which results in lower efficiency. The problem is more serious in large scale solar PV plants as the thermal losses could damage the switching devices. Lower switching frequency further reduces the switching losses which makes the proposed solution to integrate large scale PV system in the grid more attractive. Therefore, modulation techniques based on pre-computed Pulse Width Modulation (PWM) switching patterns such as Selective Harmonics elimination-PWM (SHE-PWM) method is applied on three-phases, three -level NPC topology because the generated harmonic content can be previously known and optimized as much as possible [10], [11],[20-22].

In selective harmonics elimination technique, a sinusoidal ac output voltage is produced for adjusting fundamental component within a modulation range and specific harmonics (usually low order) are selectively eliminated. But the biggest challenge to utilize the SHE methodology is to explain the switching angles from a set of nonlinear equations which may exhibits unique solution, multiple solutions or no solution in different range of modulation [12]. The methods commonly used to solve these equations are normally categorized as numerical methods, Algebraic methods and the Artificial Intelligence based optimization methods. In this context, the paper dealt modulation techniques based on pre-computed pulse width modulation (PWM) switching patterns using Jacobin function to optimize the PWM angle in SHWPWM. A 3 level and NPC inverter, is taken for the above said SHE-PWM schemes.

II. GRID TIES SOLAR PV BASED SYSTEM WITH NPC MLI

The grid tied solar energy system need not to have energy stotrage system and integration of PV system only have to meet the power quality requirement for its integration[13]. The only requirement is that the grid should not be polluted under such integration and hence it should conform IEEE-591 standard[14], [15].Among different multilevel inverter topologies, NPC is most extensively studied, used and investigated because of its inherent advantages[16], [17]. The most important advantages includes reduced switching losses, small output current ripples and reduced leakage compensation problems.

In this paper, a CHB and NPC inverter is used for interfacing between the Solar PV systems. A constant voltage is obtained from the PV system and DC to DC converter operated with maximum power point tracking.

2.1 Three-phase Three-level NPC-MLI

Figure.1 shows the 3-phase 3-level NPC MLI, which consist of 12 switch and 6 diodes. The Figure.2 shows the working of an NPC inverter in different modes. Table-1 shows the switching states and different outputs.

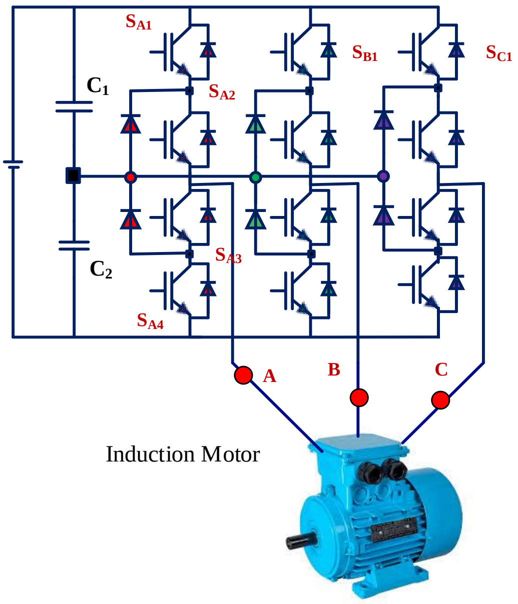


Figure 1 3-level NPC inverter system

Table 1: Switching states of a 3-level NPC inverter

Output voltage (V_{out})	S_1	S_2	S_3	S_4
$+V_{dc}/2$	1	1	0	0
0	0	1	1	0
$-V_{dc}/2$	0	0	1	1

Mode (a): Only S_2 is turned on and rest are turned off. In this case zero ouput voltage and positive output current is obtained
Mode (b): S_1 and $S_2$are turned on. In this case positive ouput voltage and positive output current is obtained
Mode (c): only S_3 is turned on. In this case zero ouput voltage and negative output current is obtained
Mode (c): Both S_3 and S_4 are turned on. In this case negative ouput voltage and negative output current is obtained

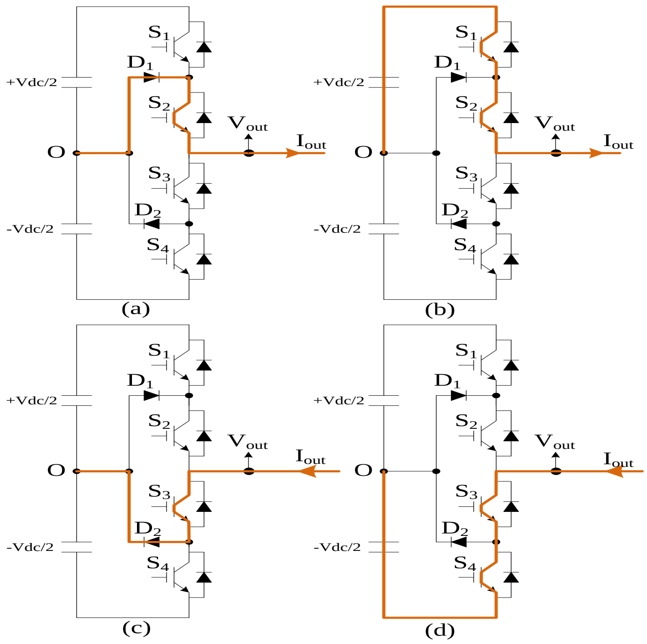
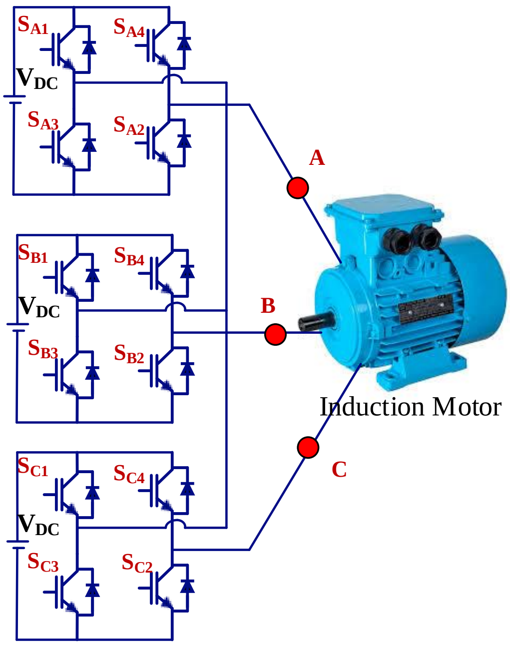


Figure 2 voltage and currents in different states

2.2 Three-phase Three-levelCBH- MLI

3 Level CBH



(b)

Figure 3 3-phase 3-level CHB-MLI

Similar to NPC MLI, for CHB uses 12 switch for making 3-level three phase circuit as shown in Figure 3. Since this MLI typehas series power conversion cells, the scaling ofpowerand voltage level can be done easily. Due to the series connection of output terminals of H-bridges, isolation of DC sourcesis must for allH-bridges.The ensuing the AC voltage output is produced based on the process of addition of generated voltages in different H-bridge cells. Based on the different combinations of four switches $S1_A$, S_{2A}, S_{3A}, and $S_{4A,}$ each single-phase H-bridge generates three voltage levels as $+V_{dc}$, 0, $-V_{dc}$ by connecting the DC source to the AC output. The CHB-MLI exploits two discrete DC sources per phase and generates an output voltage with 3-levels. To obtain $+V_{dc}$, S_{3B} and S_{2A} switches are turned 'ON', whereas $-V_{dc}$ level can be obtained by turning 'ON' the S_{2A} and S_{1B}. The output voltage will be 0 by turning 'ON' S_{1A} and S_{3A} switches or S_{3B} and S_{2A} switches as shown in the Figure.3.

Several high switching frequency modulation schemes such as space vector modulation (SVPWM)andsinusoidal pulse width modulation (SPWM) have been applied and successfully tested on NPC in the past[18]. In this paper Low switching frequency (50-800 Hz) is designed and then applied over the NPC inverter which is most suitable for high power application.

III. Selective Harmonics elemination PWM Problem Formulation

The Figure.4 shows a quarter wave symmetrical output voltages waveform having nine switching's in a quarter periods of 3-level NPC and 3-level CHB inverter. The corresponding output voltages are obtained by having the switching transitions as discussed in section 2.

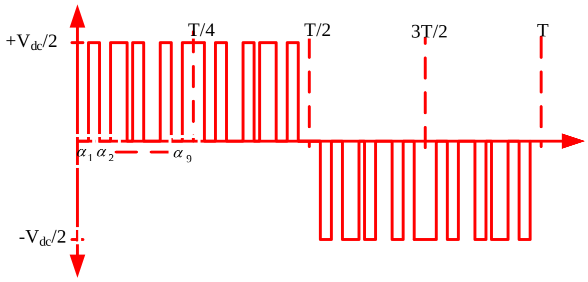


Figure.4. Quarter wave symmetrical 3 level output waveforms

To analyze the output waveform shown in Figure.3, Fourier series method is used. The general Fourier series (FS) expansion is given by equation (1)

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

FS coefficients are given by equation (2)

$$a_0 = \frac{1}{T}\int_0^T f(t)dt$$

$$b_n = \frac{2}{T}\int_0^T f(t)\sin(n\omega t)dt$$

$$b_n = \frac{2}{T}\int_0^T f(t)\sin(n\omega t)dt \quad (2)$$

Since the Waveform is having odd quarter wave symmetry, the analysis in one quarter (T/4) is sufficient to analyze the full waveform. Also, due to odd wave symmetry*$a_0=0$, $an=0$* and there will be no even component in the output. The coefficient b_n, after simplification is given by equation (3), where n represents harmonic order and Total number of switching taking place for a quarter period.

$$b_n = \begin{cases} \frac{4V_{dc}}{n\pi}\sum_{k=1}^{N}(-1)^{k+1}\cos(n\alpha_k)\ , \text{ for odd } n \\ 0\ , \text{ for even } n \end{cases} \quad (3)$$

For a balanced three phase system the triplenharmonics need not to be considered for elemniation because it the triplen harmonics will get cancelled automatically from the output waveform. Therefore the final output voltage as sum of several harmonics component of the waveform and can be given by equation.By having N switching angles in a quarter cycles, N-1 harmonics can be eliminated possibly from the output voltage waveform when obtaining desired fundamental output voltage. Generally lower order harmonics are considered for elimination as they are difficult to be filtered and causes filter of large ratings at output. Considering only lower order non triplen odd harmonics for elimination we obtain set of transcendental non linear equations given by,

$$V_{Out} = \sum_{n=1}^{\infty}\left[\frac{4V_{dc}}{n\pi}\sum_{k=1,5,7...}^{N}(-1)^{k+1}\cos(n\alpha_k)\right]\sin(n\omega t)$$

$$\left.\begin{aligned} &\sum_{k=1}^{N}(-1)^{k+1}\cos\alpha_k - m = 0 \\ &\sum_{k=1}^{N}(-1)^{k+1}\cos(5\alpha_k) = 0 \\ &\dots \\ &\sum_{k=1}^{N}(-1)^{k+1}\cos(n\alpha_k) = 0 \end{aligned}\right\} \quad (4)$$

Where m is known as modulation index and given by equation (5). V1 is the fundamental component required and V_{1max} is the maximum value of the fundamental that can be

Next section will present a technique to solve equations (4) and (5) simultaneously.

$$m = \frac{V_1}{V_{1\,max}} \quad (5)$$

VI. ITERATIVE SHE SOLVING ALGORITHM

Newton Raphson method, a numerical based iterative technique is implemented to calculate the switching angles. Here it is implemented in an unusual way, where any random initial guess in quarter i.e. 0 to π/2is assumed and the algorithm is executed in a discrete fashion. If there is ananswer for the equation set given by (6), the algorithm converges to the zero, otherwise the converges is not meet zero. The number of iterations (*j*) and tolerances in switching angles and maximum of the harmonics functions considered for stopping criteria of the algorithm. Normally the algorithm converges in 100 iterations to a good tolerance ($\varepsilon=10^{-8}$).

1. Assume any random initial of switching angles α_k^j at *j=0*.
2. Calculate the non-linear system matrix *F* and the N×N Jacobian Matrix *J*at α_k^j

$$F = \begin{bmatrix} \sum_{k=1}^{N} (-1)^{k+1} \cos \alpha_k - m = f_1 \\ \sum_{k=1}^{N} (-1)^{k+1} \cos(5\alpha_k) = f_2 \\ \cdots \\ \sum_{k=1}^{N} (-1)^{k+1} \cos(n\alpha_k) = f_N \end{bmatrix} \quad (6)$$

$$J = \begin{bmatrix} \frac{\partial f_1}{\partial \alpha_1} & \frac{\partial f_1}{\partial \alpha_2} \cdots & \frac{\partial f_1}{\partial \alpha_N} \\ \frac{\partial_2}{\partial \alpha_1} & \frac{\partial f_2}{\partial \alpha_2} \cdots & \frac{\partial f_2}{\partial \alpha_N} \\ \vdots & \vdots & \vdots \\ \frac{\partial f_N}{\partial \alpha_1} & \frac{\partial f_N}{\partial \alpha_2} \cdots & \frac{\partial f_N}{\partial \alpha_N} \end{bmatrix} \quad (7)$$

3. Compute updated value of switching angles in iteration j by $\alpha^{(j+1)} = \alpha^{(j)} - J^{-1(k)} / F^{(k)}$
4. Perform $\alpha^{j+1} = \mathrm{mod}\,(\alpha^{j+1}, \pi/2)$ and $sort\,(\alpha^{j+1})$ to ensure $0 < \alpha_1 < \alpha_2 < \cdots < \alpha_N < \pi/2$
5. Stopping criteria for the iterations

   i. $\left|\Delta \alpha_k^j\right| < \varepsilon_i \quad i = 1,2,3\cdots$ (absolute value)

   ii. $\left|\Delta \alpha_k^{j+1} - \Delta \alpha_k^j\right| < \varepsilon_i \quad i = 1,2,3\cdots$

   iii. $\max \left|f(\alpha_k^j)\right| < \varepsilon_i \quad i = 1,2,3\cdots$

   iv. $\left|f(\alpha_k^{j+1}) - f(\alpha_k^j)\right| < \varepsilon_i \quad i = 1,2,3\cdots$

6. If algorithm converges to a solution plot the switching angles with corresponding m.
7. Change m and repeat the process to cover whole range.

The large size Jacobian matrix is evaluated by numerical technique known as column wise by finite differences method. The MATLAB function for its computation is shown in table .2.

$$\%\,THD = \sqrt{\left[\sum_{n=5,7,11,13\cdots}^{100} \left(\frac{V_n}{V_1}\right)^2\right]} \times 100 \quad (8)$$

For each solution set, the computed total harmonic distortion (THD)in output line voltage using equation (8).

Table- 2 Jacobian function in Matlab

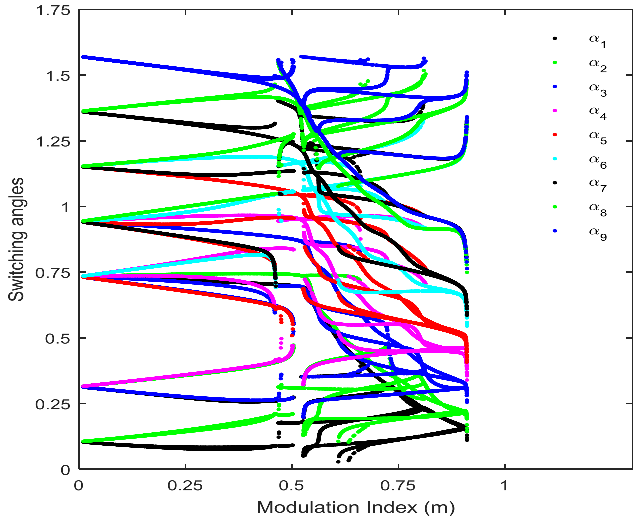
```
function [J]=jacobian (F, α)
n=length(α);
f=feval(F, α);
eps=1.e-8; % convergence check
α _rate= α;
for i=1: n
α_ rate (i)= α_rate rate(i)+eps;
J(:,i)=(feval(F, α_value)-f)/eps;
α_rate (i)= α(i);
end
```

V. SIMULATION RESULTS AND DISCUSSION

The mathematical equations for PWM output waveforms have been derived in section (3). The iterative numerical technique discussed in section (4) has been applied to obtain all the possible solution in the whole range of modulation (m). For illustration of the technique, nine switching angles in a quarter are considered and a programmed in MATLAB has been developed to evaluate the possible switching angles at different modulation. The non-triplen lower order harmonics considered for elimination are 5^{th} to 23rd and 25^{th}. The Figure. 4 shows the Switching angles at different modulation. Thus, the next lower order harmonics in the output waveform is 29^{th}, i.e. 1450 Hz, which can be easily filtered out with small rating filters.

Figure.4 shows all the possible solution of switching angles. It is clear that there is multiple solution, unique solutions and no solutions in different range of modulation (0<m<1).

Figure5shows the percent THD for different solution in the whole range of modulation. It is evident that among different solution at a particular modulation (m), some solution gives lower THD than other solutions. Also at lower modulations the percentage THD is more than the higher modulation index. The CHB and NPC are gave a similar performance.



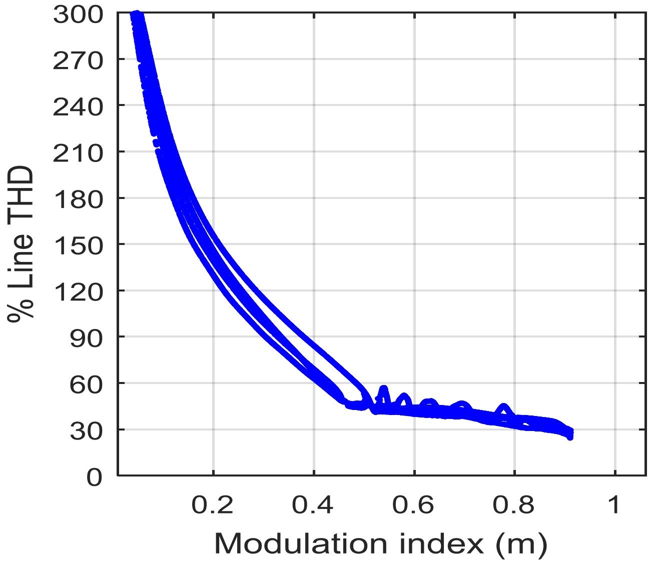


Figure.5. % THD at different solutions

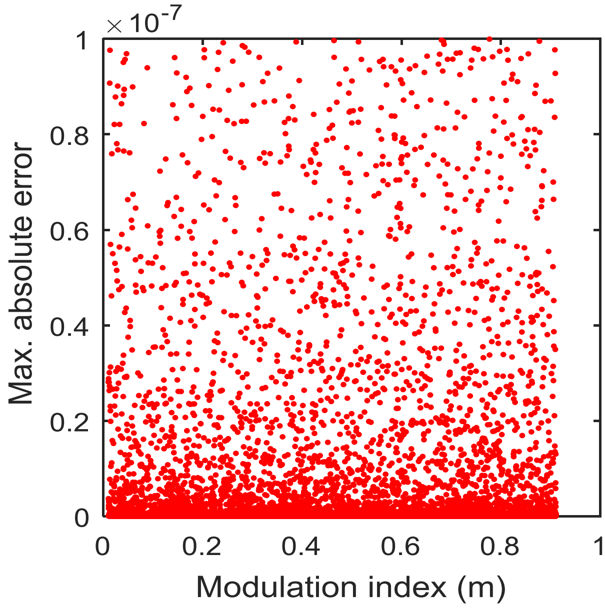


Figure. 6. % THD at different solutions

Figure (6) shows the maximum absolute error in the targeted harmonics for elimination as given by eqn. (9). It shows very good accuracy as in most of the cases it converges to zero value.

$$abs\ \ error = \max(f_1, f_2, \cdots f_9) \qquad (9)$$

As the system equations in selective harmonics elimination are nonlinear, therefore it exhibits multiple solutions in some range. Itcouldsee from Figure. 4, that at modulation index m=0.70, three sets of solution exist and are given in table (2). It is clear that some solution exhibits lower THD than other. The type solution selection is purely application dependent e.g. one can select the solution by considering minimum width of the pulse or based on THD etc.At m=0.70 the harmonics spectrum for all the three sets of solution are shown in Figure. (7) -(9). The harmonics spectrum does not contain the lower order harmonics considered for elimination and the first predominant harmonics is of 29th order i.e. 1450 Hz. Also, the widths of these pulses are different for different set of solutions. If one has to consider lower THD, then solution can be considered optimum.

Table. 3. possible solutions at m=0.7

Solution	**α_1=**	**α_2=**	**α_3=**	**α_4=**	**α_5=**	**α_6=**	**α_7=**	**α_8=**	**α_9=**	**% THD**	**Max. Error**
I	0.20	0.30	0.36	0.95	0.99	1.25	1.32	1.43	1.52	34.03	5.6×10^{-10}
II	0.11	0.19	0.28	0.44	0.56	1.12	1.19	1.33	1.41	39.01	9.8×10^{-11}
III	0.26	0.29	0.36	0.76	0.83	0.94	0.99	1.44	1.52	36.04	7.8×10^{-7}

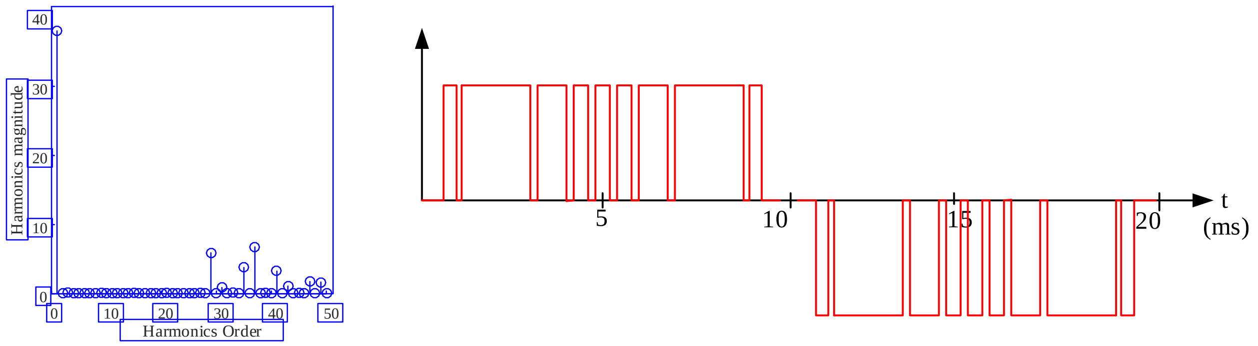


Figure .7. Harmonics spectrum and output waveform for solution-I

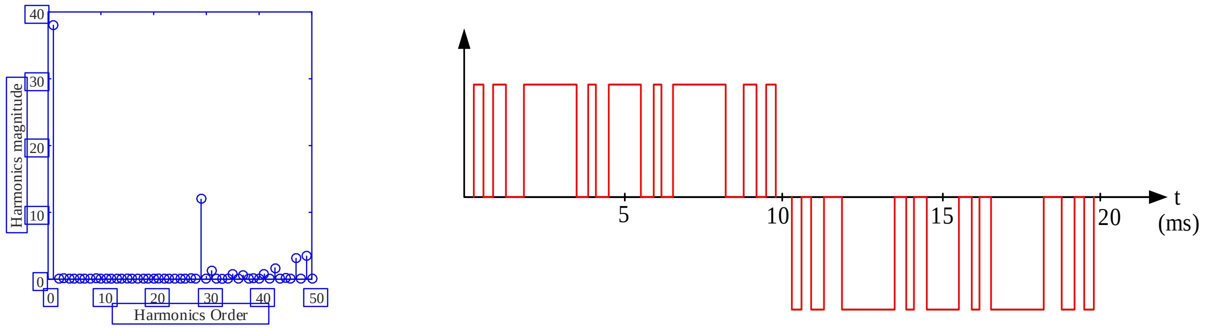


Figure.8. Harmonics spectrum and output waveform for solution-II

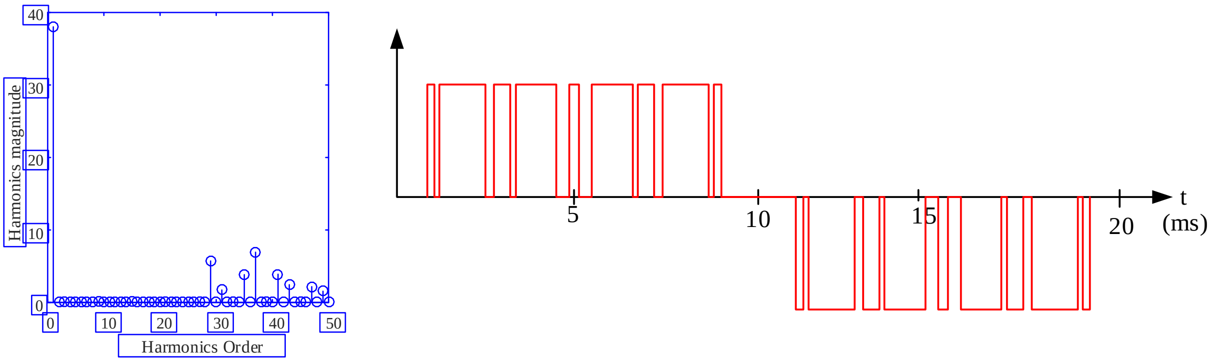


Figure 9. Harmonics spectrum and output waveform for solution-III

VII. EXPERIMENTAL RESULTS

The experimental setup MLI inverter is shown in figure. 10. The inverter. The 12 SK 150 MLI 066 T IGBT Modules SEMITOP 4 IGBT is used in all three legs of NPC-MLI. The input capacitor is used as 1000microFarad and RL load is used in the three-star connected manner. The proposed PWM is coded in FPGA based controller using MATLAB/SIMULINK blocks.Using HDL Coder, the MATLAB SIMULINK blocks are automatically generating VHDL for Xilinx FPGA.This approach supports with HDL Coder and Xilinx Design Group, and synthesizesthe design and program the bit stream on FPGA board automatically. A VHDL test bench is generated by HDL Coder for functional verification. The proposed PWM is investigated in both three-phase, three-level CBH and NPC MLIs.The PWM dead is set as 5microsec, which is included in FPGA implementation code. The mathematical equation for PWM a programme in MATLAB has been developed through Xilinx system and the corresponding bit file is converted into VHDL code [19]. The generated PWM has a possible switching angle at different modulation. When the DC-link is applied as 100V, the MLI inverter is tested for table 3 solutions and measured the live voltage and THD values. The simulation results are closer to investigational results. The Figure. 11 shows the experimental outcomes of m= 0.67.

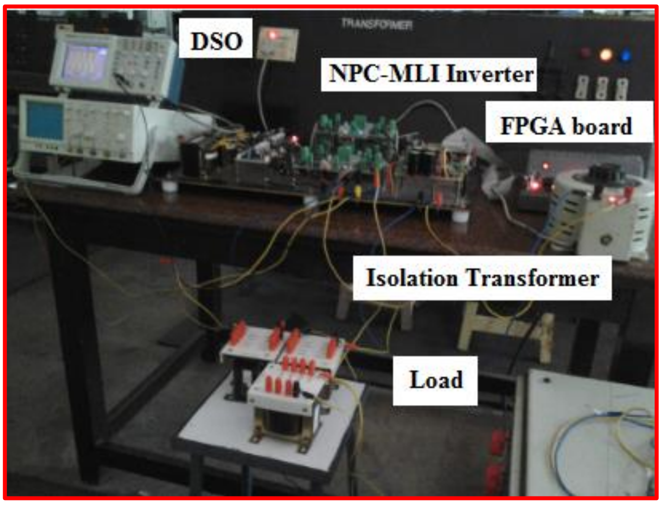
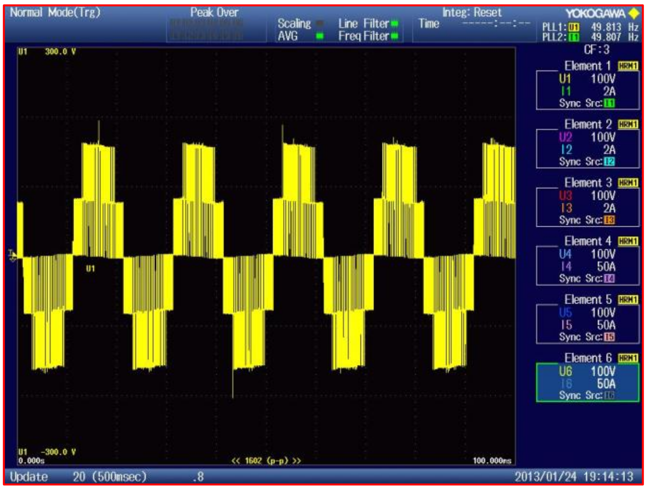
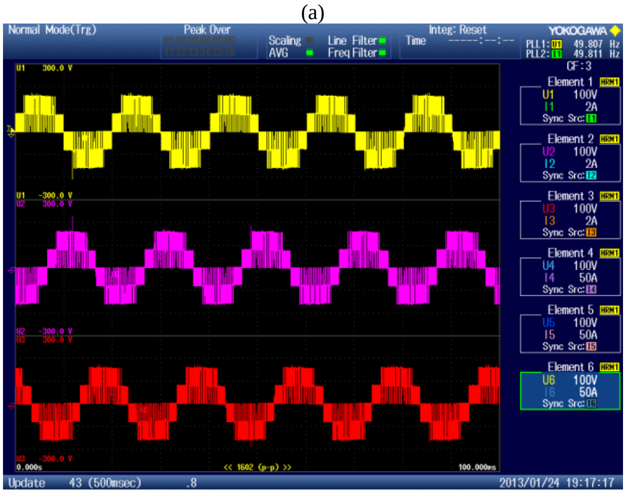


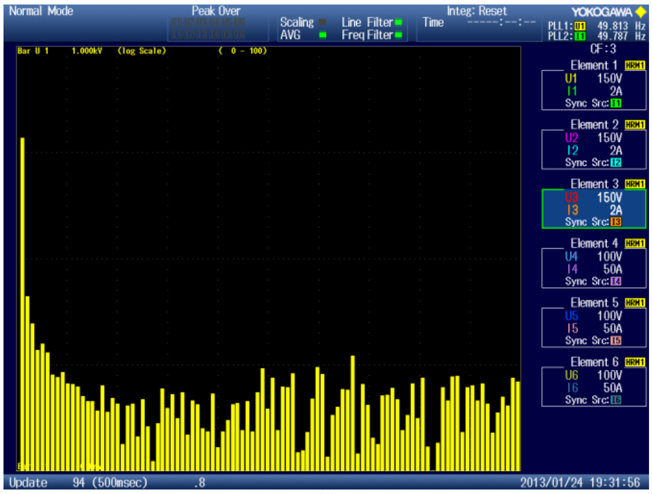
Figure .10. Experimental setup



(a)



(b)



(c)

Figure .11. Experimental results for m=0.67; (a). Line voltage, (b) THD profile

Here, the line-voltage and percentage THD is much close to the simulation results. Similar, percent THD for different solution in the whole range of modulation is same as simulation results. It is evident that among different solution at a particular modulation (m), some solution gives lower THD than other solutions. Also at lower modulations the percentage THD is more than the higher modulation index.

VIII. Conclusion

In this paper, a low switching frequency based Selective harmonics elimination technique for 3 levels NPC inverter in gird tied solar PV system is proposed. This topology can be very useful in large scale solar PV systems as lower rating switching devices can be utilized and switching losses can be minimized. Fourier series analysis has been carried out for 9 switching angles in a quarter cycles. These nonlinear transcendental equation sets are solvedby an iterative technique called Newton Raphson method. The Newton Raphson method is applied in slightly different way as different convergence parameters are considered. The modulation index of the order of 10^{-4} is considered to evaluate all the possible solutions. The result shows multiple solutions, unique solutions and no solutions in different range of modulation. The selection of a particular solution is application dependent. The output voltage result also shows the absence of selected lower order non-triple odd harmonics for elimination. In this paper, very accurate solutions are only considered and reported. More solution can be accumulated if the convergence criteria are relaxed further. Since at higher Modulation indices the THD is low, but at very low modulation indices the THD is very high, so it opens scope for further research on hybrid PWM.

References

[1]. B. Singh, C. Jain, S. Goel, A. Chandra, and K. Al-Haddad, “A multifunctional grid tied solar energy conversion system with ANF based control approach,” 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Sep. 2015.

[2]. D. Leuenberger and J. Biela, "PV-Module Integrated AC Inverters (AC Modules) with Subpanel MPP-Tracking," IEEE Trans. Power Electron., vol. 8993, no. c, pp. 1–1, 2016.
[3]. C. Hu, Q. Wang, hui Yan, and Y. Yang, "Research on neutral-point potential balancing and control method for three-level NPC inverter," JOURNAL OF ELECTRONIC MEASUREMENT AND INSTRUMENT, vol. 2009, no. 6, pp. 74–81, Dec. 2009.
[4]. H. Gupta, A. Yadav, and S. Maurya, "Multi carrier PWM and selective harmonic elimination technique for cascade multilevel inverter," 2016 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB), Feb. 2016.
[5]. A. Choudhury, P. Pillay, and S. S. Williamson, "A Hybrid PWM-Based DC-Link Voltage Balancing Algorithm for a Three-Level NPC DC/AC Traction Inverter Drive," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 3, no. 3, pp. 805–816, Sep. 2015.
[6]. "Modular multilevel converters and other multilevel converter topologies and applications," 2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE), Jun. 2014.
[7]. J. Rodriguez, J. Pontt, E. Silva, J. Espinoza, and M. Perez, "Topologies for regenerative cascaded multilevel inverters," IEEE 34th Annual Conference on Power Electronics Specialist, 2003. PESC '03.
[8]. M. Metry, Y. Liu, R. S. Balog, and H. Abu-Rub, "Model predictive control for maximum power point tracking of quasi-Z-source inverter based grid-tied photovoltaic power system," 2017 IEEE 26th International Symposium on Industrial Electronics (ISIE), Jun. 2017.
[9]. C.Bharatiraja, R.Latha, S.Jeevananthan, S.Raghu and S.S. Dash, "Design And Validation Of Simple Space Vector PWM Scheme For Three-Level NPC– MLI With Investigation Of DC Link Imbalance Using FPGA -IP Core ", Journal of Electrical Engineering , vol.13, no. 1, pp 54-63, March 2013.
[10] C. Uniuersity, "Programmed Pwm Techniques To Eliminate Harmonics," *IEEE Trans. Ind. Appl.*, vol. 26, no. 2, 1988.
[11] M. S. A. Dahidah, G. Konstantinou, and V. G. Agelidis, "A Review of Multilevel Selective Harmonic Elimination PWM: Formulations, Solving Algorithms, Implementation and Applications," *IEEE Trans. Power Electron.*, vol. 30, no. 8, pp. 4091–4106, 2015.
[12] V. G. Agelidis, S. Member, A. Balouktsis, and I. Balouktsis, "Multiple Sets of Solutions for Harmonic Elimination PWM Bipolar Waveforms : Analysis and Experimental Verification," *IEEE Trans. Power Electron.*, vol. 21, no. 2, pp. 415–421, 2006.
[13] C. Bharatiraja, S. Jeevananthan, J.L. Munda, and R. Latha, "Improved SVPWM vector selection approaches in OVM region to reduce common-mode voltage for three-level neutral point clamped inverter," International Journal of Electrical Power & Energy Systems/ Elsevier, vol. 79, no. 1, pp. 285–297, Oct. 2016.
[14] J. Napoles, J. I. Leon, R. Portillo, L. G. Franquelo, and M. A. Aguirre, "Selective harmonic mitigation technique for high-power converters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 7, pp. 2315–2323, 2010.
[15] M. Najjar, A. Moeini, M. K. Bakhshizadeh, F. Blaabjerg, and S. Farhangi, "Optimal Selective Harmonic Mitigation Technique on Variable DC Link Cascaded H-Bridge Converter to Meet Power Quality Standards," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 4, no. 3, pp. 1107–1116, 2016.
[16] F. Z. Peng, W. Qian, and D. Cao, "Recent advances in multilevel converter/inverter topologies and applications," *2010 Int. Power Electron. Conf. - ECCE Asia -, IPEC 2010*, pp. 492–501, 2010.
[17] S. Calligaro, F. Pasut, R. Petrella, and A. Pevere, "Modulation techniques for three-phase three-level NPC inverters: A review and a novel solution for switching losses reduction and optimal neutral-point balancing in photovoltaic applications," *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, pp. 2997–3004, 2013.
[18] C. Bharatiraja, S. Jeevananthan and JL munda "Timing Correction Algorithm for SVPWM Based Diode-Clamped MLI Operated in overmodulation Region", in IEEE journal of Selected topics in Power Electronics applications. 10.1109/JESTPE.2017.2723518. (in press).
[19]. C. Bharatiraja, R. Latha, "A 3-dimensional SVPWM algorithm, its FPGA-implementation for multilevel inverters", in Journal of Electrical Engineering. vol.15, no.2, pp. 61-70, Dec 2015.
[20]. C. Bharatiraja, S.Raghu, Thanga Raj Chelliah, and JL munda "Design and Implementation of Fourth Arm for Elimination of Bearing Current in NPC-MLI fed Induction Motor Drive", in IEEE Transactions on Industry Applications.DOI: 10.1109/TIA.2017.2759204, (Article in press). [SCI -2.937 IF], 2017.
[21]. Santhakumar, C., Shivakumar, R., Bharatiraja, C., Sanjeevikumar, P. "Carrier shifting algorithms for the mitigation of circulating current in diode clamped MLI fed induction motor drive ", in International Journal of Power Electronics and Drive Systems, vol.8, no.2, pp. 844-852, June 2017.
[22]. C.Bharatiraja, S.Jeevananthan., Latha, R., "FPGA based practical implementation of NPC-MLI with SVPWM for an autonomous operation PV system with capacitor balancing", in International Journal of Electrical Power and Energy Systems/ Elsevier, vol. 61, pp.489-509, Oct 2014