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# Minimization of Switching Losses in Grid Interfaced PV Inverters using SHE Modulation Strategy

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#### **Abstract**

Grid interfacing of multi-megawatt photovoltaic inverters is getting a closer attention in recent past. It is always a hard and challenging task for the engineers as there are certain priorities to be taken while interfacingPV cells to grid without which there will bean unsatisfactory operation of the system will taken. Somehow for high power and medium voltage grid inverters the priorities like IEEE and IEC standards, satisfaction of grid codes and switching losses are to be strictly considered. Mitigation of switching losses is the active area of research for the PV systems. To meet such requirements weare using the traditional and conventional modulation strategy like SHE (Selective Harmonic Elimination). This paper focus on the reduction of switching losses with the help of new implementation technique for SHE that uses the third harmonics to have the switching angles over 90°, which also increases the modulation index. The Selective harmonic elimination strategy can allow the grid connected inverters to operate using a switching frequency less than 1 KHz while it is still able to provide satisfactory operation like simplicity in operation, independent control of active and reactive powers which is not possible in other cases. To validate potential benefits of SHE, it is compared with THI PWM which is controlled with an operating frequency of 2 KHz.

**Keywords:** Grid Interfaced PV Inverters, Pulse Width Modulations (PWMs), Selective Harmonic Elimination (SHE), Switching Losses, THI PWM (Third harmonic injection PWM)

### 1. Introduction

The efficient and effectiveness usage of generated power can be done by interfacing the PV cells with the grid. However, the technical aspects both from the PV system side and from the power system utility grid side must be satisfied to validate the reliability of the utility gridandsafety of the PV installer<sup>1,2</sup>. Understanding the technical needsfor interconnected grid and solving the issues likeelectromagnetic interference, harmonic distortion requirements, islanding detection and switching losseswhich are very much important issues for wide range applicability of PV systems. In general grid interconnection of PV systems is achieved through by theinverter, which handles the task i.e., conversion of dc power produced from PV panels to alternating power utilized for ordinary power supply to electric loads. Therefore inverter system is an important for grid connected PV systems.

The developments of flexible ac transmission system devices, medium voltage drives, and various kinds of generating stations that are distributed, have given greater scope and opportunities for implementing highpower and medium-power inverters. In mentioned applications the switching frequency of pulse-width modulation is limited by electromagnetic interference by high dv/dt and switching losses3. Hence in order to get rid of these problems Selective Harmonic Elimination (SHE) based optimal pulse width modulations are being implemented in multilevel inverters and two level inverters to minimize the switching frequency and the total harmonic distortion. Most gird connected PV systems are not apt for the high power due to the usage of higher switching frequency (high switching losses and voltage stress). Almost of the studies use sinusoidal or space-vector pulse width modulation to have control over the inverters. The use of sinusoidal strategy doesn't fully utilize linkeddc voltage, which results in lowering power

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density. SVPWM increases semiconductor utilization, dc link voltage and power density, but have difficulties while operating in medium voltage distribution systems where ac faults and unbalance operations are very high. Hence the need for the use of conventional strategy SHE is preferred. Selective Harmonic Elimination Pulse-Width Modulation (SHE-PWM) has been mainly developed for two- and three-level converters in order to achieve lower Total Harmonic Distortion (THD) in the voltage output waveform. The main challenge associated with SHE-PWM techniques is to obtain the analytical solution of nonlinear transcendental equations that have trigonometric terms which results in providing multiple sets of solutions.

### 2. Pulse Width Modulation for Grid-connected Inverters

Many applications such as industrial heating, lighting control and speed control of induction motors require variable ac voltage. Generally triacs or anti parallel connected thyristors are used as power converters in such systems. These converters which are simple, reliable and cost effective however suffer from various drawbacks such as increase in harmonic level contents and poor power factor especially at lower output voltages<sup>4,5</sup>. The system performance can be further improved using various harmonic elimination techniques which can be accomplished by a microprocessor leased firing scheme.

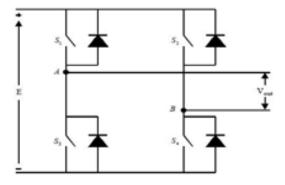
The method of giving fixed dc input voltage to the inverter and obtaining a controlled ac output voltage by adjusting the on-off periods of the inverter components is termed as "Pulse Width Modulation" (PWM). The width of the pulse is subjected to modulation to have inverter output voltage and to reduce its harmonic content.

Switching angles at fundamental frequency for a multilevel inverter are obtained by solving the equations of selective harmonic elimination in a way that the fundamental voltage is obtained along with the elimination of desired and certain lower order harmonics. The equations are non linear and transcendental in nature which may exist simple, multiple or sometimes no solutions for a particular modulation index value. If we try to solve the transcendental equations using iterative numerical techniques, only single solution set is obtained even there exists multiple solution sets. There are also other approaches like theory of symmetric polynomial, resultants method gives all possible solutions but these are

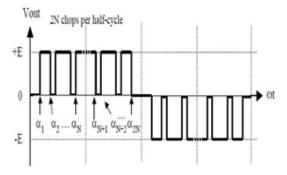
high in complexity. This paper uses the Newton-Raphson method for finding the solution to the transcendental equations which gives the possible solutions with any random initial guess and for any number of levels of multilevel inverter. The solution with the least THD value is to be considered.

# 3. Selective Harmonic Elimination Technique

The selective harmonic elimination PWM technique at present used to synthesize an output waveform of both full-bridge inverter andhalf-bridge inverter. A three-level SHE PWM produced by a full-bridge inverter is considered here in this section<sup>7</sup>. An H-bridge or full-bridge voltage source inverter, which is having one dc source and four switches,is shown in Figure 1. The output states of the waveform like zero, positive and negative can be obtained. Per quarter part of the output waveform should be chopped N times i.e., each and every switch is thus switched N times per cycle to generate such anoutput waveform.



**Figure 1.** H-bridge or Full bridge voltage source inverter.



**Figure 2.** 3 level output waveform (generalized).

The full bridge inverter as mentioned above has three states of operation<sup>8</sup>. Consider the three-level SHE PWM waveform (generalized) depicted in Figure 2. Let the total number of switching angles per quarter-cycle be N. The output waveformwhose amplitude equals to E is assumed to be odd quarter wave symmetry.

As odd quarter-wave symmetry, the even harmonics and the dc component will be equal to zero. Hoftand Patel used the Fourier series for the three levels SHE PWM as follows:

$$V_{\text{out}}(\omega t) = \sum_{n=1}^{\infty} a_n \sin(n\omega t)$$
(1)

Where

$$a_n = \frac{4E}{n\pi} \sum_{k=1}^{N} (-1)^{k+1} \cos(n\alpha_k) \text{ For odd n}$$
 (2)

N is the number of the switching angles per quarter.  $\alpha_k$  is the switching angle, which must satisfy the following condition:

$$\alpha_1 < \alpha_2 < \alpha_3 \dots < \alpha_N < \frac{\pi}{2} \tag{3}$$

Where n is the harmonic order and E is the amplitude of the dc source.

## 3.1 Newton's Method to Solve SHE PWM Switching Angles

From equation (2), the nonlinear equation system of SHE PWM waveform can be written as follows

$$\cos(\alpha_1) - \cos(\alpha_2) + \cos(\alpha_3) - \dots \pm \cos(\alpha_n) = \frac{\pi}{4}M$$
(4)

$$\cos(3\alpha_1) - \cos(3\alpha_2) + \cos(\alpha_3) - \dots \pm \cos(3\alpha_n) = \frac{3\pi}{4E}h_3$$
 (5)

$$\cos(n\alpha_1) - \cos(N\alpha_2) + \dots \pm \cos(N\alpha_n) = \frac{N\pi}{4E} h_n$$
 (6)

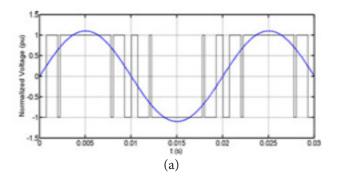
Where

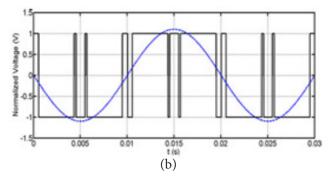
M is the modulation index and  $M = \frac{h_1}{E}$ 

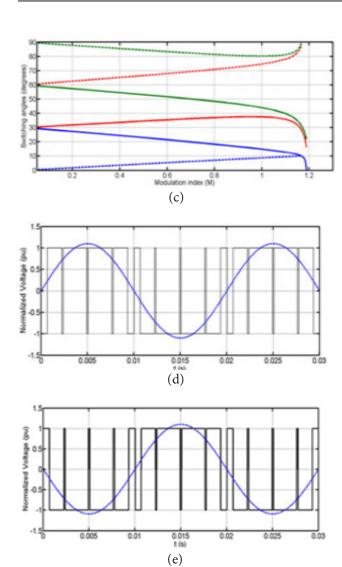
The equations from (4) to (6), cosine terms of  $\alpha_n$  are positive with odd N and negative with even N. To have the control in the amplitude of the fundamental component M is given in equation (4). From the equations, N-1 s harmonics can be eliminated from the output waveform by equating (5) to zero. The lowest odd harmonic is to be eliminated from a single-phase system, whereas in three-phase system lower non-triple harmonics are to be eliminated.

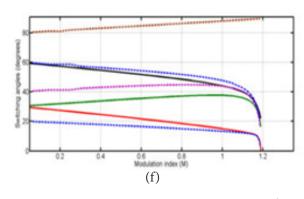
#### 3.2 Selective Harmonic Elimination

The Figure 3(a) and 3(b) shows output voltage of two level converters relative to supply midpoint which is normalized. When SHE is employed for controlling the inverter with three notches for fundamental voltage adjustment and elimination of fifth and seventh harmonics all the switching angles Figure 3(a) can be seen in between 0 and 60° (solution1) as shown in Figure 3(c) (solid line). The modulation index which can attain through this is 1.1884. This modulation index is possible by solving optimization problem9. The switching angles will be  $\alpha_1 < \alpha_2$ ,  $\alpha_2 < \alpha_3$ ,  $\alpha_3 < \frac{\pi}{E}$ , the arrangement in Figure 3(b) is for solution 2 and produces the switching angles distributed over 90° with  $\alpha_2 < \alpha_3$  located between 60° and 90°. The modulation index for solution 2 is 1.16 which is lower than solution1. In addition it can be observed that solution 2 produces a fundamental voltage which is 180° out of phase to that of solution 1. For the same fundamental voltage this can be observed in Figure 3(b) as seen most of first cycle of the wave. This is very much critical in the SHE implementation. For increasing the modulation index for solution 2 we are injecting 3rd harmonic content. When a fourth angle is added to 3rd harmonic, the maximum modulation index using solution1 remains at 1.1884 shown in Figure 3(f).









**Figure 3.** Figure 3. (a), (b) Phase voltage when 5<sup>th</sup> and 7<sup>th</sup> harmonics are eliminated, (c) Switching trajectories for solution 1 and 2 (solid line for solution 1, dotted for 2), (d) Phase voltage when 5<sup>th</sup> and 7<sup>th</sup> harmonics removed and 3<sup>rd</sup> harmonic M3/5 (e) Voltage when 5th and 7<sup>th</sup> harmonics eliminated and 3<sup>rd</sup> harmonic is M3/5 and (f) Switching trajectories with and without 3rd harmonic for solution 1.

#### 3.3 Third Harmonic Injection PWM

Figure 4 shows THI natural sampling implementation, with magnitudeo of third harmonic equal to 1/6 the fundamental voltage<sup>10</sup>. In this the THI is implemented based on regular sampling with 2KHz switching frequency.

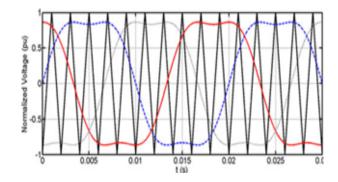


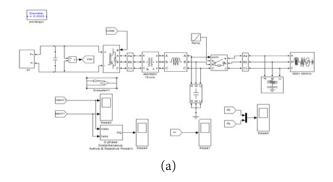
Figure 4. Implementaion of carrier based THI PWM.

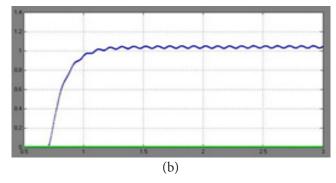
# 4. Simulation Results and Discussion

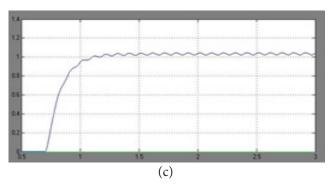
This section deals with the results and their analysis after simulation. For the better validation of Selective Harmonic Elimination technique the results of the both i.e., grid connected PV inverter with SHE and THI PWM are compared. The simulation parameters of a multimegawatt PV inverter are to be given to each block and are to simulated to get the results. The simulation parameters of PV inverter are tabulated in Table 1.

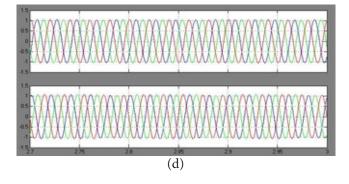
**Table 1.** Simulation parameters of a multi-megawatt PV inverter

PARAMETERS		VALUES
Converter power rating		25
DC link voltage		20
AC voltage (line-to-line in KV)		11
Active power capability (MW)		20
Reactive power capability in MVAR		15
Grid frequency (KHz)		50
Switching frequency	THI-PWM	2
	SHE	0.95
Current control proportional gain $K_{p}$	THI-PWM	70
r	SHE	220
Current control integral gain,K	THI-PWM	3000
	SHE	5000









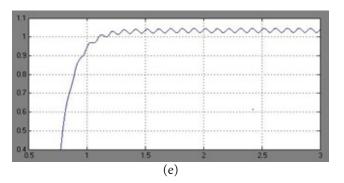


Figure 5. (a) Simulation block for SHE PWM implementation for grid interconnected PV system, (b) Variation of active current for inverter at full load, (c) Reactive and active power of a PV inverter with the grid, (d) Grid output voltage and output current (normalized) and (e) Modulation index with SHE implemented (PI controller).

Figure 5 (b) and 5(c) gives the variation of active current and active and reactive power of a grid connected PV system, when it is controlled with o SHE technique with a switching frequncy of 1KHz the normalized grid output voltage and current can be seen in Figure 5(d).

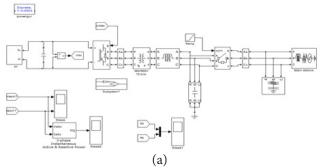


Figure 6. (a) Simulation diagram of THI PWM implementation for grid interconnected PV system, (b) Variation of active current when PV inverter operates at full load, (c) Active and reactive power PV inverterexchanges with the grid and (d) Normalized grid voltage and current.

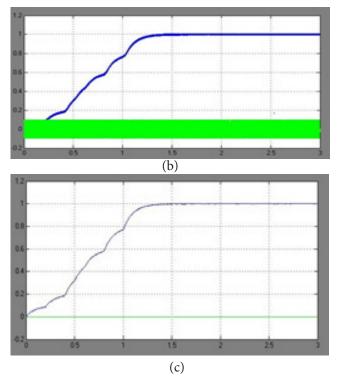
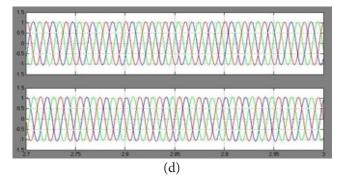


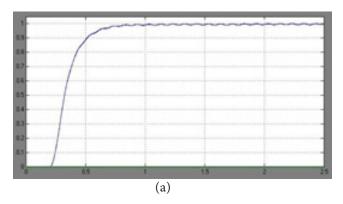
Figure 6(b) and 6(c) Shows the variation of active and reactive powerand active current of a grid interfaced PV inverter controlled with THI PWM technique with switching frequency of 2KHz. Figure 6(d) shows the normalized grid voltage and currents.

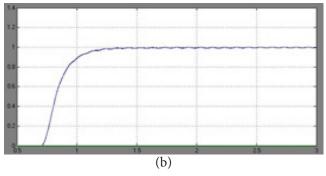


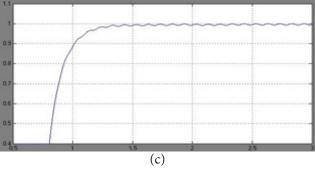
The results show that SHE can be used in the place of carrier based PWM strategies which are used to control grid connected PV inverter, and maintain all the controlling features achieved by carrier based strategies. Figures 5(a) and 6(a) Shows the simulation diagram of SHE and THI PWM. The results are obtained when the active power current component  $I_d$  is varied from 0 to 1.0 p.u. (25 MVA and 11 KV based). Note that SHE

produces the similar performance characteristics that of a THI PWM at approximately half the switching frequency, including ac voltage, system dynamics and current waveform quality<sup>11,12</sup>.

When PI controller is replaced with the fuzzy the outputs are shown inbelow Figures 7(a), 7(b), and 7(c).







**Figure 7.** (a) Variation of active current for PV inverter at full load, (b) Active and reactive power inverter exchanges with the grid and (c) Modulation index when controlled with SHE (Fuzzy based).

For further illustration of potential gains the switching losses with THI PWM and SHE modulation strategies for a 25 MVA PV inverter are tabulated in Table 2.

Table 2. Summary of switching losses with THI PWM and SHE modulation strategies for a 25 MVA PV inverter

Operating	P=20MW	Q=15 MVAr	20 MW at
condition	at 0.8 power	at zero power	unity power
	factor lagging	factor	factor
SHE	190.6 KW	190.2 KW	88.7 KW
THI-PWM	401.2 KW	400.4 KW	401.2 KW

### 5. Conclusion

This paper investigated the suitability of SHE, applied to high-power medium-voltage grid connected inverters used as interfacing units for large scale integration of renewable energy sources. It has been demonstrated that SHE doesn't violate any inverter functionalities i.e., it has the same control features when the inverter is operating with the carrier based strategies. The SHE produces similar performance characteristics to that of THI PWM at approximately half the switching frequency, which includesac voltage, system dynamics, and current waveform quality. In addition this paper has shown that contrary to traditional SHE implementation, with the adjustment of third harmonic magnitude a solution which is universal is produced for harmonic elimination equations that generally spreads the switching angles over 90°. This feature can be used to simplify the SHE realization at high modulation indices when more harmonics are eliminated.

#### 6. References

1. Khajehoddin SA, Bakhshai A, Jain P. The application of the cascaded multilevel converters in grid connected photovol-

- taic systems. IEEE Canada Electrical Power Conference; 2007. p. 296-301.
- 2. Zhe C, Guerrero JM, Blaabjerg F. A review on the state of power electronics for wind turbines. IEEE Trans Power Electron. 2009 Aug; 24(8)1859-75.
- 3. Yang B, Li W, Zhao Y, He X. Design and analysis of a gridconnected photovoltaic power system. IEEE Trans Power Electron. 2010 Apr; 25(4):992-1000.
- 4. Kjaer SB, Pedersen JK, Blaabjerg F. A review of single-phase grid-connected inverters for photovoltaic modules. IEEE Trans Ind Appl. 2005 Sept-Oct; 41(5):1292-306.
- Daher S, Schmid J, Antunes FLM, Multilevel inverter topologies for stand-alone PV systems. IEEE Trans Ind Electron. 2008 Jul; 55(7):2703-12.
- 6. Fei W, Wu B, Huang Y. Half-wave symmetry selective harmonic elimination method for multilevel voltage source inverters. IET Power Electron. 2011; 4:342-51.
- 7. Dahidah MSA, Agelidis VG, Rao MV. On abolishing symmetry requirements in the formulation of a five-level selective harmonic elimination pulse-width modulation technique. IEEE Trans Power Electron. 2006 Nov; 21(6):1833-7.
- Feel-Soon K, Sung-Jun P, SuEog C, Cheul UK, IseT. Multilevel PWM inverters suitable for the use of stand-alone photo voltaic power systems. IEEE Trans Energy Conversation. 2005 Dec; 20(4):906-15.
- Koutroulis E, Blaabjerg F. Design optimization of grid-connected PV inverters. 26th Annual IEEE Applied Power Electronics Conference and Exposition; 2011 Mar; Fort Worth. p. 691-8.
- 10. Ahmadi D, Ke Z, Cong L, Yi H, Jin W.A universal selective harmonic elimination method for high-power inverters. IEEE Trans Power Electron. 2011Oct; 26(10):2743-52.
- 11. Zhang Y, Adam GP, Lim TC, Finney SJ. Williams BW. Voltage source converter in high voltage applications: Multilevel versus twolevel converters. 9th IET International Conference AC and DC Power Transmission; 2010 Oct; London. p. 1-5.
- 12. Wu T-F, Chang C-H, LinL-C, Kuo C-L. Power loss comparison of single- and two-stage grid-connected photovoltaic systems. IEEE Trans Energy Conversation. 2011 Jun; 26(2):707-15.