Modified SHE for Grid Connection

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Abstract

This paper presents an improved selective harmonics elimination technique for PV assisted single phase grid-tied pulse width modulated (PWM) voltage source inverter (VSI). The switching angles are determined offline through numerical techniques and stored in microcontroller memory as a function of modulation index \( m_d \) for online application. For multiple solution, the solution which leads to lower change of switching angles (\( \alpha \)) from the previous \( m_d \), is considered for storing in the processor memory. This leads to less number of sections for the processor when a piecewise mixed model is considered for storing the entire switching angle curve. This technique is well suited for limiting voltage THD in two level grid connected VSI with L-C filter. The verification of theoretical concept is done in laboratory prototype of PV (500 W) connected to grid-tied PWM inverter. The control environment is realized in embedded FPGA interfaced national instrument hardware.
An Improved Selective Harmonics Elimination Technique for PV Assisted Single Phase Grid-Tied PWM Inverter

Abstract-- This paper presents an improved selective harmonics elimination technique for PV assisted single phase grid-tied pulse width modulated (PWM) voltage source inverter (VSI). The switching angles are determined offline through numerical techniques and stored in microcontroller memory as a function of modulation index ma for online application. For multiple solution, the solution which leads to lower change of switching angles (α) from the previous ma, is considered for storing in the processor memory. This leads to less no. of sections for the processor when a piecewise mixed model is considered for storing the entire switching angle curve. This technique is well suited for limiting voltage THD in two level grid connected VSI with L-C filter. The verification of theoretical concept is done in laboratory prototype of PV (500 W) connected to grid-tied PWM inverter. The control environment is realized in embedded FPGA interfaced national instrument hardware.

Index Terms-- Selective Harmonics Elimination (SHE), Pulse Width Modulated (PWM) Inverter.

I. INTRODUCTION

In last decade application of renewable energy sources such as PV and wind has escalated in power industry to combat climate change. But these sources are highly intermittent in nature and creates a challenge for continuous power supply [1]. Inverters are used for grid integration for solar PV system. Grid-tied inverters can be either current source inverter (CSI) or voltage source inverter (VSI) type [2]. Effectiveness in MPPT of series connected PV string can be enhanced by using CSI [3]. But this approach is having a major limitation of increased conduction loss in semiconductor switches compared to VSI for similar rating [4]. Again, ability of CSI with strict grid code such as fault ride through is questionable. In the last decade use of VSI like two level and multilevel for grid interfacing had investigated intensively [5]. Multilevel inverters have problem of inability to counter partial shading and it requires a large number of series connected PV cell to maintain DC link voltage. Cascaded multilevel inverter is better alternative but it reduces life of PV cell as it exposes low frequency ac component [6-8]. Real time selective harmonics elimination scheme is tested with PV tied multilevel inverter as proposed by F. Filho et.al [9]. But it has deficiency of increased complexity with feedback control. On the counterpart, two level inverters are still reliable for grid connected systems. However, they have limitations like switching losses and relatively low-quality output voltage [10]. To meet the strict grid code like IEEE 1574, IEC61727 [11] while interfacing medium voltage grid connected inverter, different advanced modulation strategies are used. Carrier based sinusoidal PWM or space vector PWM is mostly used for inverter control. Sinusoidal PWM is incapable of utilizing full DC link voltage, thus power density is less [12]. Compared to sinusoidal PWM, space vector PWM enhances use of semiconductor and DC link voltage. It increases switching frequency and has limitation of stable operation under unbalance operation in AC side [13]-[16]. Thus, finding a proper modulation strategy is challenging to meet strict grid code [16] with individual harmonics as a percentage of fundamental [11]. There are different topologies of filter presented in recent literatures for grid connected inverter where L-C, L-C-L filter are popular to support these grid code restrictions [17-18]. Different control topologies of inverter are researched to work with L-C-L filter while connected to grid. The main problem of L-C filter connected to inverter, is higher voltage THD compared to L-C-L filter of same size [19]-[24]. These mentioned issues of PWM techniques, grid codes and standard requirements can be eliminated by using traditional SHE based PWM [24-25]. The major issue of the SHE PWM techniques are that the solution of the transcendental equations requires numerical techniques to be solved. The online application becomes difficult due to increased computational burden in processor.

In the proposed work an improved selective harmonics elimination technique for PV assisted single phase grid-tied PWM inverter is implemented. Piecewise mixed linear model for storing switching angles for different modulation indexes (ma) is adopted in proposed control. This technique is simple in implementation and provide low voltage THD at less filter size.

II. PV ASSISTED GRID-TIED INVERTER SYSTEM MODELLING

Single phase grid tied PV model comprises of 500W solar PV, 100 Ah lead acid battery, buck-boost converter and inverter system. These components are modelled using dynamic equations in PSIM 9.1.1 simulation environment.

A. PV Modelling:

For simplicity in the analysis of single diode model of PV cell is considered [1] as shown in Fig.1. Thus, the output current from PV is

\[ I = I_{ph} - I_{sh} \]

where

\[ I_{ph} = I_{sc} \left( \frac{V + IR}{nV_T} - 1 \right), \quad I_{sh} = \frac{V + IR}{R_{sh}} \]

Thus, \[ I = I_{ph} - I_{sh} \left( \frac{V + IR}{nV_T} - 1 \right) \] and \[ V = \frac{TK}{q} \]
B. Buck-Boost Converter:

Buck-boost converter is PV interfaced converter responsible to fix steady output voltage before inverter. The modelling equations [1] are,

$$\frac{di_c}{dt} = \frac{R_c (1+D)-R_L}{C} \left( \frac{(D-1)}{L_L} \right) i_c + \frac{D}{L_E} V_g$$

$$v_c = -(1-D)R_c \left[ \frac{D}{L_E} V_g \right]$$

C. Voltage Source Inverter Modelling (VSI):

Linear inverter control with SHEPWM is applied for grid integration. Therefore, d-q model [26] is adopted in this work as shown in Fig. 2. The dynamic equations are,

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} u_d \\ u_q \end{bmatrix} \frac{1}{L} \begin{bmatrix} 1 & 0 \\ \frac{r_L}{L} & \frac{1}{L} \end{bmatrix} \begin{bmatrix} r_0 & Z+r_c \\ \frac{V_n}{V_s} & 0 \end{bmatrix} \begin{bmatrix} 1 \\ \frac{1}{L} \end{bmatrix} \frac{r_c}{Z+r_c} \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$\frac{d}{dt} \begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} 1 \\ \frac{1}{C} \end{bmatrix} \begin{bmatrix} 0 & -\omega_0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix}$$

Transformation matrix helps to find d-q model of single phase VSI from equation (3).

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = T \begin{bmatrix} X_d \\ X_q \end{bmatrix}$$

As parasitic elements are very small thus these are neglected in d-q modelling of VSI.

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} u_d \\ u_q \end{bmatrix} \frac{1}{L} \begin{bmatrix} 0 & -\omega_0 \\ \omega_0 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \begin{bmatrix} 1 \\ \frac{1}{L} \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix}$$

D. Lead Acid Battery Model with Current tracking:

The total system arrangement is shown in Fig. 6. Battery management is necessary due to intermittency of PV power. CIEMAT based dynamic battery model [27] is adopted in this work as shown in Fig. 3. Since the novelty of the work is not on battery management, on SOC information is not discussed in details.

III. PROPOSED ALGORITHM OF SELECTIVE HARMONICS ELIMINATION TECHNIQUE

The proposed SHE technique is and its effectiveness on implementation is discussed below.

A. Harmonics Elimination in Bridge Inverter:

A generalized method to eliminate any number of harmonics is done by switching the voltage waveform. For a periodic inverter voltage waveform with unit amplitude this relationship is easily derived without losing generality. The voltage waveform for M number of switching per quarter cycle is shown in Fig. 4.
The waveform has property of half wave symmetry and fourier series of the waveform is,

$$ f(n_0 t) = \sum_{n=1,3,5} [b_n \sin(n_0 t) + a_n \cos(n_0 t)] $$

From Fig.3, \( a_0 = 0 \), \( a_{2M+1} = \pi \) and \( a_b < a_1 < a_2 < \ldots < a_{2M+1} \), the values of \( a_b \) and \( b_b \) is easily derived utilizing half wave symmetry property. For all odd values of \( n \),

$$ a_n = \frac{4}{n \pi} \left[ -\sum_{k=1}^{2M} (-1)^k \sin(n \alpha_k) \right] $$

and,

$$ b_n = \frac{4}{n \pi} \left[ 1 + \sum_{k=1}^{2M} (-1)^k \cos(n \alpha_k) \right] $$

The equation of \( a_n \) and \( b_n \) are functions of \( 2M \) variables \((a_1, a_2, a_3, \ldots, a_{2M})\). In order to obtain an unique solution for the \( 2M \) variables, \( 2M \) equations are required. By equating \( M \) harmonics to zero value \( 2M \) equations are derived from \( a_n \) and \( b_n \) equations. Again, applying quarter wave symmetry in Fig. 4 it is obvious that

$$ \alpha_k = \pi - \alpha_{2M+k+1} $$

for \( k=1,2,3 \) and \( a_b=0 \).

Thus,

$$ b_n = \frac{4}{n \pi} \left[ 1 + 2 \sum_{k=1}^{M} (-1)^k \cos(n \alpha_k) \right] $$

(7)

M harmonics can be eliminated by solving \( M \) equation obtained from Eq.7. Newton-Raphson based linearized model is adopted to solve this equation to get switching angles for a modulation index.

The Eq. 7 can be generalized as

$$ f_i(\alpha_1, \alpha_2, \ldots, \alpha_M) = 0; \text{ for } i=1,2,3, \ldots, M. $$

Initially \( \alpha^0 = [\alpha_1^0, \alpha_2^0, \ldots, \alpha_M^0]^T \) can be calculated with guess value within 0 to \( \pi/2 \). Second step is to calculate \( f(\alpha^0) = f^0 \).

Linearizing the Eq. 7 about \( \alpha^0 \)

$$ f^0 + \left[ \frac{\mathrm{df}^0}{\mathrm{d}\alpha} \right] \delta \alpha = 0 $$

where,

$$ \left[ \frac{\mathrm{df}^0}{\mathrm{d}\alpha} \right] = \begin{bmatrix} \frac{\mathrm{df}_1}{\mathrm{d}\alpha_1} & \frac{\mathrm{df}_1}{\mathrm{d}\alpha_M} \\ \vdots & \vdots \\ \frac{\mathrm{df}_M}{\mathrm{d}\alpha_1} & \frac{\mathrm{df}_M}{\mathrm{d}\alpha_M} \end{bmatrix} $$

Evaluating at \( \alpha^0 \) and \( \delta \alpha = [\delta \alpha_1, \delta \alpha_2, \ldots, \delta \alpha_M]^T \) solution of linearized Eq.7 is found. This process is again repeated to determine accurate switching angles \((\alpha^1 = \alpha^0 + \delta \alpha)\). The degree of accuracy is determined for small value of error \( \epsilon \).

It is necessary condition to satisfy the final switching angles to follow \( 0 < \alpha_1 < \alpha_2 < \ldots < \alpha_M < \frac{\pi}{2} \)

$$ \left[ \frac{\mathrm{df}}{\mathrm{d}\alpha} \right] = \begin{bmatrix} \frac{\mathrm{df}_1}{\mathrm{d}\alpha_1} & \frac{\mathrm{df}_1}{\mathrm{d}\alpha_M} \\ \vdots & \vdots \\ \frac{\mathrm{df}_M}{\mathrm{d}\alpha_1} & \frac{\mathrm{df}_M}{\mathrm{d}\alpha_M} \end{bmatrix} $$

In order to solve matrix of Eq.7 must be non-singular. This condition is violated is anyone \( \alpha_1, \alpha_2, \ldots, \alpha_M \) is equal to zero when the domain of solution is within the interval \([0, \pi/2]\). Also, is any two \( \alpha \) are equal, two columns of the matrix shall be identical, except for the sign, which may be opposite. The rank of the matrix in that case reduced to \( M-1 \), and the matrix will be singular.

Thus, the condition \( 0 < \alpha_1 < \alpha_2 < \ldots < \alpha_M < \frac{\pi}{2} \) ensures the non-singularity of matrix and a meaningful solution of Eq.7.

In the proposed algorithm as shown in Fig. 5, when the solution of a particular modulation index \( (m_0) \) leads to a drastic change of \( \alpha \) from previous \( m_0 \), a repetitive set of initial guesses is tried to achieve \( \alpha \) nearer to previous value of \( m_0 \). In the proposed algorithm 100 times repetition of initial value of \( \alpha \) is taken. This is required to reduce the number of sections to store variation of \( \alpha \) with \( m_0 \) which ensures reduced memory burden of the processor. In some case there is no solution for a particular \( m_0 \) and then discontinuation of \( \alpha \) leads to unsuccessful while implemented for online application.

Fig. 4. Generalized SHE PWM voltage output of Inverter.

Fig. 5 Flowchart of proposed SHE Technique.
In the proposed technique the amplitude of higher order harmonics is maintained at lower value while eliminating lower order harmonics. This technique ensures a continuous $\alpha$ value with modulation index ($m_d$) variation. Again, it also lowers the switching frequency helping to maintain THD at lower value and suitable for online closed loop system application.

**B. The Effectiveness of the Proposed SHE Technique:**

The proposed technique is superior over other SHE techniques in literature as it has several advantages like (a) linear change in modulation index ($m_d$). (b) Increase in modulation index ($m_d$) range (c) Piecewise mixed model suitable for closed loop operation.

(a) **Linear change in modulation index ($m_d$)**

Sometimes solutions of equation 7 leads to discontinuation of $\alpha$ for a particular modulation index. Thus, it creates complexity in practical implementation.

(b) **Increment in modulation index range**

SHE technique tends to produce switching angles in narrow range closed to zero especially when $m_d$>1. The proposed technique produces linear variation in switching angle above modulation index 1 as shown in Fig. 8. Typically, up to $m_d$=1.16 operation is possible with the proposed SHE technique.
### IV. SIMULATION AND EXPERIMENTAL RESULT

Simulation in PSIM 9.1.1 and hardware study is done to verify effectiveness of proposed SHE on single phase grid tied PV system as shown in Figs.6 and 10.

### Table I

<table>
<thead>
<tr>
<th>Software</th>
<th>Computational Burden [Software and hardware]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>For 3(^{rd}) and 5(^{th}) harmonics</td>
</tr>
<tr>
<td></td>
<td>Error</td>
</tr>
<tr>
<td>Conventional SHEPWM</td>
<td>3.2x10(^{-7})</td>
</tr>
<tr>
<td>Proposed SHEPWM</td>
<td>4.1x10(^{-7})</td>
</tr>
</tbody>
</table>

### Fig. 9 switching angle with modulation index (m\(_d\)) variation [conventional-blue line] and switching angle with modulation index (m\(_d\)) variation [Proposed SHE with Mixed Model-Red line].

Thus, these piecewise mixed equations memory burden to microprocessor is reduced. Comparison of computational burden between proposed SHEPWM and conventional SHEPWM is given in Table-I.
Fig. 11. Line voltage after L-C filter.

Table II

<table>
<thead>
<tr>
<th>Harmonics</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
<th>11</th>
<th>13</th>
<th>15</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage (%) of Fundamental Voltage Harmonics @Simulation Result</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 12 (a) shows the experimental switching waveform for eliminating 5th and 7th harmonics. The harmonics elimination is obtained by programming in Lab-view c-RIO 9082 on 9401 module, and the switching angles are 16.247°, 22.068° respectively.

Fig. 13. (a) Switching waveform for eliminating 5th, 7th, 11th and 13th harmonics (b) Inverter output waveform for eliminating 5th, 7th, 11th and 13th harmonics.

The inverter output voltage using SHE PWM is shown in Fig. 18 (a). The FFT of the output voltage is shown in Fig. 14 (c). The Voltage THD value is 5.7 % and measured in power quality analyzer Aplab PQA2100E and individual harmonics contents are listed in Table IV.

The corresponding inverter output voltage is shown in Fig. 12 (b). Similarly the switching angles for eliminating 5th, 7th, 11th, and maintaining 13th harmonics within lower value as discussed in section III are found as 10.545°, 16.092°, 30.904° and 32.866° respectively as shown in Fig. 13 (a). The inverter output voltage is shown is Fig. 13 (b).
Fig. 14. (a) Voltage output after L-C filter (Transformer input). (b) FFT of voltage using conventional PI control of inverter. (c) FFT of voltage using proposed SHEPWM control.

It is found that the with same filter size THD value with conventional control of inverter is higher i.e. 11.1 % as shown in Fig. 14 (b). The comparative study shown in Table-III shows the effectiveness of the proposed control and it is found better than L-C-L type filter-based control with less complexity.

### Table-III

<table>
<thead>
<tr>
<th>PI Control with L-C Filter</th>
<th>SHE PWM with L-C Filter</th>
<th>Control with L-C-L Filter [18-19]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L:90uH., C:3uH</td>
<td>L:90uH., C:3uH</td>
<td>L:5.5mH, L2:1mH, C: 20uF.</td>
</tr>
<tr>
<td>Voltage THD: 11.1%</td>
<td>Voltage THD:5.7%</td>
<td>Voltage THD:5.067%</td>
</tr>
</tbody>
</table>

It is clear from Table-III that SHEPWM based linear control with L-C filter gives comparable voltage THD result with proportional resonant (PR) controller-based L-C-L filter system. Classical PI control with sinusoidal PWM inverter control with L-C filter has voltage THD is about 11.1% which is around 5% and 6% more than other methods. Thus, the proposed SHEPWM based control is capable of replacing complex PR control scheme with LCL filter. Though proposed method has 0.633% more voltage THD, it can be further improved by increasing capacitor value from 3uF to (5-10) uf. The proposed control scheme is modelled and implemented in 2-kHz switching frequency. The L-C filter size can be further minimized by increasing switching frequency. But this comes with complexity in determining firing angle for eliminating 3rd and 5th harmonics with different modulation index.

### Table-IV

<table>
<thead>
<tr>
<th>Harmonics</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
<th>13</th>
<th>17</th>
<th>27</th>
<th>33</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>0.05</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
<td>0.15</td>
<td>0.25</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Total control of source side PV, battery and inverter as shown in Fig. 15 is done in Lab view c-RIO 9082 using system parameter in Table V.

### Table-V

<table>
<thead>
<tr>
<th>Inverter (VA)</th>
<th>PV Panel</th>
<th>Battery</th>
<th>Active Power</th>
<th>Reactive Power</th>
<th>Frew</th>
<th>Freq Hz</th>
<th>Tr Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>500W</td>
<td>100Ah</td>
<td>500W</td>
<td>300Var</td>
<td>2</td>
<td>50</td>
<td>1:10</td>
</tr>
</tbody>
</table>

Fig. 15. (a) Single phase grid tied VSI with lead acid battery. (b) 500-Watt PV panel.

![Fig. 15](image1)

![Fig. 15](image2)
Fig. 16 shows the online PV voltage, PV power and common DC link stable voltage. The dynamic pulse of MPPT is shown in Fig. 16(ii)(c).

During load change DC link voltage, and current changes stably as shown in Fig. 17 (a) and (c) respectively.

![Diagram](image)

Fig. 17 (a) DC bus voltage for step load change. (b) Grid tied Active power and reactive power. (c) Stable Line voltage and line current after L-C filter during load change [Resistive].

V. CONCLUSION

In the presented work an improved selective harmonics elimination technique for PV assisted single phase grid-tied PWM inverter is implemented. This technique gives best result in voltage THD (5.7%) with low value L-C filter compared to conventional PI based control of same filter size (11.1%). It is effective as control scheme is simple unlike L-C-L based filter system and low voltage THD value while connected to single phase grid. The proposed technique is tested in 500W single phase grid tied solar PV system.

The achievements of applying the proposed techniques are

(a) Low voltage THD is achieved using proposed piecewise linear model of SHEPWM suitable for online application.

(b) L-C filter size is comparable to PR controlled LCL filter system.

(c) Easy control scheme and low-cost microcontroller (TMS320F28379D) can easily be used for single phase PV tied grid connected system.

(d) Flexibility in mitigating individual harmonics content using less burden on processor.

REFERENCES


