Real time Implementation of SHE PWM in Single Phase Matrix Converter using Linearization Method

P. Subha Karuvelam† and M. Rajaram*

Abstract – In this paper, a real time implementation of selective harmonic elimination pulse width modulation (SHEPWM) using Real Coded Genetic Algorithm (RGA), Particle Swarm Optimization technique (PSO) and a new technique known as Linearization Method (LM) for Single Phase Matrix Converter (SPMC) is designed and discussed. In the proposed technique, the switching frequency is fixed and the optimum switching angles are obtained using simple mathematical calculations. A MATLAB simulation was carried out, and FFT analysis of the simulated output voltage waveform confirms the effectiveness of the proposed method. An experimental setup was also developed, and the switching angles and firing pulses are generated using Field Programmable Gate Array (FPGA) processor. The proposed method proves that it is much applicable in the industrial applications by virtue of its suitability in real time applications.

Keywords: Single Phase matrix converter, Selective harmonic elimination pulse width modulation, Real coded genetic algorithm, Particle swarm optimization, Total harmonic distortion.

1. Introduction

Many applications such as industrial heating, light control, soft start induction motors and speed control of AC motors require continuously varying AC voltage from a fixed AC voltage source. AC voltage regulator with phase angle control and integral cycle control techniques is commonly employed for these requirements. The advantages of these techniques are simplicity, cost effectiveness, reliability and ability to control large amount of power. On the other hand, the delayed firing angle in these schemes causes the discontinuity in load current and higher value of lower order harmonics. To mitigate these problems, PWM AC choppers are preferred. In the PWM AC choppers, high switching frequency-based PWM is preferred for the system in which switching losses are endurable. Carrier-based Sine PWM (SPWM), Space Vector PWM (SVPWM) are examples of high switching frequency PWM techniques. Carrier based PWM technique is implemented in various ways such as sub-oscillation method and modified sub-oscillation method [1]. Low switching frequency based PWM is preferred for the system in which switching losses are intolerable and can tolerate the harmonics to certain extent. The low switching frequency is typically around the fundamental frequency of the output voltage. Selective Harmonic Elimination PWM (SHEPWM), Optimal Minimization of the Total Harmonic Distortion (OMTHD) and Optimized Harmonic Stepped Waveform (OHSW) are the examples of low switching frequency PWM techniques [1]. In these techniques, the AC chopper waveforms are analyzed using Fourier theory, and sets of nonlinear transcendental equations are derived and solved using any iterative procedure such as Newton-Rapson, Random search and Rosenbrocks method. The convergence of these techniques depends on the choice of initial values. Stochastic optimization techniques overcome the drawbacks, and they are used to find the global optimum solution with a short time searching. Colony Algorithm (BCA), Firefly Algorithm, Differential Evolution (DE) are some of the optimization techniques [2-11]. These techniques are used for SHE in AC/AC converter also [9-11]. Hopfield neural network-based approach is also used to solve the SHEPWM problem [12].

In Selective harmonic mitigation (SHMPWM), the selected harmonic contents are restricted to the values specified by grid codes EN50160 and CIGRE WG 36-05 [13]. In SHEPWM technique, N-1 number of harmonics can be eliminated for N switching angles but in SHMPWM, N2 number of harmonics can be limited to the values specified by any grid code for N switching angles.

Venturini & Alesina presented the basic configuration of the power circuit as a matrix of bidirectional switches that connect each load phase with the source phase. The authors introduced the name ‘matrix converter’ and proposed control theory known as Venturini modulation [14]. Different control techniques known as modified Venturini modulation, scalar control strategy, space vector modulation and carrier based modulation technique were proposed [15-21]. Zuckerberger introduced the single phase matrix converter for direct AC-AC conversion [22]. SPMC has extended its operation to inverter, boost...
rectifier, buck-boost rectifier and step up/down frequency conversion [23]. It employs the force-commutating or self-commutating devices.

In this paper, RGA and PSO are used for the SHE in SPMC. From the switching angle trajectory of RGA and PSO, a new technique called linearization method is proposed in this paper. The fundamental voltage, THD and the harmonic contents of the proposed technique are compared with RGA and PSO, and the results are tabulated.

2. Circuit Analysis

The single phase matrix converter consists of four switches SW1, SW2, SW3, SW4 and these are illustrated in Fig. 1(a). Bidirectional power flow in AC to AC converter demands the bidirectional switches that are capable of blocking voltages in both polarities and conduction of current in both directions. A discrete semiconductor fulfilling these requirements is not available in practice, and hence an antiparallel IGBT diode pair is used here. Theoretically, the switching is simultaneous and instantaneous. In real time, the finite switching times and delays in the circuit are taken into account.

The input voltage and the output voltages are given by

\[ v_i(t) = 2V_s \sin \omega t \]  
\[ v_o(t) = 2V_o \sin \omega t \]  
\[ v_o(t) = R_i + L \frac{dv_o(t)}{dt} \]

The switching sequences for the output frequency of 50 and 100 Hz are summarized in Table 1. At anytime “t”, two switches are in ON state.

Fig. 1(b) shows the ideal synthesized output voltage waveform of single phase matrix converter with the output frequency of 50Hz. The waveform possesses N switching angles between 0 and \( \frac{\pi}{2} \). Due to the square wave symmetry in the output waveform, all the even harmonics are eliminated and the odd harmonics alone are present in the output. In SHE technique with N switching angles, control of fundamental voltage and the elimination of N-1 selected lower order harmonics are done. In this paper, seven switching angles are generated.

Table 1. Switching sequences

<table>
<thead>
<tr>
<th>( f_o )</th>
<th>Mode</th>
<th>Interval</th>
<th>Switching State</th>
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<tr>
<td>50</td>
<td>Duty</td>
<td>SW1A &amp; SW4A</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Free Wheeling</td>
<td>SW3B &amp; SW4A</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Duty</td>
<td>SW1B &amp; SW4B</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Duty</td>
<td>SW1A &amp; SW4A</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Duty</td>
<td>SW3B &amp; SW4B</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Duty</td>
<td>SW2A &amp; SW3A</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Duty</td>
<td>SW1B &amp; SW4B</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Free Wheeling</td>
<td>SW2B &amp; SW3B</td>
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<tr>
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<tr>
<td>2</td>
<td>Free Wheeling</td>
<td>SW3A &amp; SW4B</td>
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</tr>
</tbody>
</table>

Fig. 1. (a) Circuit diagram of SPMC; (b) Synthesized output voltage (50Hz) of single phase matrix converter
3. Formulation of Transcendental Equations

The Fourier Series expansion of output voltage is

\[ V_o = V_m \sum_{n=1}^{\infty} \left( A_n \sin(n \omega t) + B_n \cos(n \omega t) \right) \]  \hspace{1cm} (4)

where \( A_n \) and \( B_n \) are the Fourier coefficients.

\( n \) is the order of the harmonic.

\( V_m \) is the peak value of the output voltage.

The fundamental coefficients \( A_1 \) and \( B_1 \) are expressed as

\[ A_1 = \frac{1}{2\pi} \left[ \sum_{i=1,2}^{N} \left( -1^i \left( \frac{\sin(1-n)\alpha_i - \sin(1+n)\alpha_i}{1-n} \right) \right) \right] \] \hspace{1cm} (5)

\[ B_1 = \frac{1}{2\pi} \left[ \sum_{i=1,2}^{N} \left( -1^i \left( \frac{\cos(1-n)\alpha_i - \cos(1+n)\alpha_i}{1-n} \right) \right) \right] \] \hspace{1cm} (6)

The coefficients \( A_n \) and \( B_n \) are expressed as

\[ A_n = \frac{1}{2\pi} \left[ \sum_{i=1,2}^{N} \left( -1^i \left( \frac{\sin(1-n)\alpha_i - \sin(1+n)\alpha_i}{1-n} \right) \right) \right] \] \hspace{1cm} (7)

\[ B_n = \frac{1}{2\pi} \left[ \sum_{i=1,2}^{N} \left( -1^i \left( \frac{\cos(1-n)\alpha_i - \cos(1+n)\alpha_i}{1-n} \right) \right) \right] \] \hspace{1cm} (8)

The output voltage is articulated as

\[ V_0 = V_m \sum_{n=1}^{\infty} C_n \left[ \sin(n \theta + \phi_n) \right] \] \hspace{1cm} (9)

where \( C_n = \sqrt{(A_n)^2 + (B_n)^2} \) and \( \phi_n = \tan^{-1} \left( \frac{B_n}{A_n} \right) \).

Let \( F(\alpha) \) be the objective function to be minimized and is defined as

\[ F(\alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_N) = (C_1 - MI)^2 + C_2^2 + C_3^2 + \ldots + C_{2N-1}^2 \] \hspace{1cm} (10)

With the constraint \( 0 \leq \alpha_1 \leq \alpha_2 \leq \ldots \leq \alpha_N \leq \frac{\pi}{2} \)

where modulation index \( MI = \frac{V_{\text{rms}}}{V_{\text{rms}}} \).

The objective function \( F(\alpha) \) is minimized subject to the condition in Eq. (10). Hence the desired output voltage is regulated over the range 0 to \( V_m \) by changing the modulation index, and the selected harmonics up to 13th order are eliminated.

4. Real Coded Genetic Algorithm (RGA)

Genetic algorithm is inherently parallel because of simultaneous evaluation of many points in search space. Hence GA has reduced the chance of converging in local optima and more chance to converge in global optima [24]. Initially, GA was designed to operate with binary codes. Now real coded GA is used due to their supreme behavior such as reduced computational effort, absolute precision, etc. The steps involved in RGA-based approach are illustrated.

Step 1: Random generation of the initial population

Generating \( N \) switching angles is the solution to this problem. Each switching angle is a gene represented by real numbers. There are \( N \) genes in each chromosome. Each chromosome represents the solution to the problem. Population consists of sets of chromosomes. Population is initialized with random numbers between 0 and \( \frac{\pi}{2} \).

Step 2: Evaluation of the fitness function

The objective function in this study is to minimize the selected harmonics, and hence fitness function has to be minimized. Since all optimization techniques are used only for the maximization problem, the fitness function is modified as below

\[ FN = \frac{1}{1 + F(\alpha)} \] \hspace{1cm} (11)

Fitness of each chromosome is computed.

Step 3: Generation of offspring

Offspring is a new (Child) chromosome. From the fitness value of each chromosome, best parents are selected for reproduction. In this work, tournament selection is used as selection mechanism to avoid premature convergence. The selected parents are subjected to Simulated Binary Crossover (SBX) and polynomial mutation. Self-adaptive simulated binary crossover-based RGA was successfully applied to various engineering optimization problems [25].

Simulated Binary Crossover

In SBX crossover, two children solution \( y_i^{(1)} \) and \( y_i^{(2)} \) are wrought from the parent solution \( x_i^{(1)} \) and \( x_i^{(2)} \). The SBX operator simulates the working principle of the single point crossover on binary strings.

\[ y_i^{(1)} = 0.5 \left[ (1-\beta) x_i^{(1)} + (1+\beta) x_i^{(2)} \right] \] \hspace{1cm} (12)

\[ y_i^{(2)} = 0.5 \left[ (1+\beta) x_i^{(1)} + (1-\beta) x_i^{(2)} \right] \] \hspace{1cm} (13)

The spread factor \( \beta \) is defined as the ratio of absolute difference in child solution \( y_i^{(1)} \) and \( y_i^{(2)} \) values to that of parents’ values \( x_i^{(1)} \) and \( x_i^{(2)} \).
5. Particle Swarm Optimization (PSO)

PSO is a population-based stochastic optimization technique developed by Eberhart and Kennedy inspired by the social behavior of bird flocking and fish schooling. The steps involved in PSO algorithm are given below.

Step 1: Random generation of the initial population
It begins with the initialization of particle position (switching angles) between $0$ to $\frac{\pi}{2}$ and velocities in “N” dimensional space.

Step 2: Evaluation of the fitness function
In each iteration, the particle moves according to the velocity and changes its position. The fitness function is evaluated for each particle.

Step 3: Setting Pbest and Gbest
The best position reached among the particles during their search is the particle best (Pbest). The best fitness value reached by the particle in all the searches is the Global best (Gbest).

Step 4: Updating the velocity and the position of each particle
Let $V_i$ and $X_i$ represent the velocity and the position of $i^{th}$ particle. The velocity and the position of each particle are updated as given below.

$$V_i^{k+1} = \omega V_i^k + C_1 r_1 \left( P_{best}^k - X_i^k \right) + C_2 r_2 \left( G_{best}^k - X_i^k \right)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1}$$

where $\omega$ - Inertia weight at iteration $k$, $V_i^k$ - Velocity of $i^{th}$ particle at iteration $k$, $P_{best}^k$ - Best position of $i^{th}$ particle at iteration $k$, $G_{best}^k$ - Best position of the group till iteration $k$, $\omega_{max}$ and $\omega_{min}$ are initial and final weights, $iter_{max}$ - total number of iterations.

The procedure is repeated from Step 2 till the stopping criterion is reached. The stopping criteria of RGA are applicable to PSO also. The parameters used in PSO algorithm are shown in Table 2.

Table 2. Parameters used in RGA and PSO

<table>
<thead>
<tr>
<th>Genetic Algorithm</th>
<th>PSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of Runs = 10</td>
<td>No of Runs = 10</td>
</tr>
<tr>
<td>Switching Angles = 7</td>
<td>Switching Angles = 7</td>
</tr>
<tr>
<td>Population Size = 100</td>
<td>Population Size = 100</td>
</tr>
<tr>
<td>SBX crossover constant $n_m=2$</td>
<td>Acceleration constants $C_1$ and $C_2=1$</td>
</tr>
<tr>
<td>Mutation constant $n_m=20$</td>
<td>Maximum Generation = 100</td>
</tr>
<tr>
<td>Maximum Generation = 100</td>
<td></td>
</tr>
</tbody>
</table>

1) When the number of iterations performed by the RGA reaches the value of the maximum iteration.
2) When the number of evaluations performed by the RGA reaches the maximum number of evaluation.
3) When the change in the objective function from one generation to the next successful poll is less than the objective function tolerance.

In SHE technique, initially the objective function is formulated, and the formulated function is solved either using conventional techniques or any one of the optimization techniques. In both the techniques, the switching angles are derived offline only for certain number of modulation indices due to their large convergence time. These switching angles are stored in lookup table of any controller during real-time applications. The required MI is approximated to the nearest MI which is stored in the controller and this leads to inaccurate control. The proposed linearization method overcomes this drawback.

The proposed algorithm is applicable for the system in which switching losses are intolerable and can tolerate the harmonics to the certain extent. In this technique, the objective function is not needed. From the switching angle trajectory of RGA and PSO shown in Fig. 3(a) and 3(b), it is observed that the variation of switching angles is almost linear irrespective of the number of angles [10]. Hence a pure linear switching angle trajectory is derived in LM and it shown in Fig. 4. From this trajectory, the switching angles are obtained for any modulation index. The steps involved in this technique are given below.

**Step 1**: Initialization of parameters
- Number of switching angles = $N$
- Modulation Index = $MI$
- Lower Limit $X_{1min} = 0$
- Upper Limit $X_{Nmax} = 90$

$$X_{1min} = 0 \text{ and } X_{Nmax} = 90$$  \hspace{1cm} (23)

**Step 2**: Calculation of lower and upper limits of each switching angle

$$X_{1max} = 90 / \left( \frac{N+1}{2} \right)$$  \hspace{1cm} (24)

$$X_{2min} = X_{1max}$$  \hspace{1cm} (25)

$$X_{2max} = X_{2min} + (X_{1max} / 2)$$  \hspace{1cm} (26)

$$X_{N-1min} = X_{2max}$$  \hspace{1cm} (27)

$$X_{N-1max} = X_{N-1min} + (X_{1max} / 2)$$  \hspace{1cm} (28)

$$X_{Nmin} = X_{N-1max}$$  \hspace{1cm} (29)

**Step 3**: Determination of switching angles for the given MI
For any modulation index MI,

$$X_N = \begin{cases} X_{Nmin} + \left( \frac{X_{1max}}{2} \cdot MI \right) & N = \text{Even} \\ X_{Nmax} - \left( \frac{X_{1max}}{2} \cdot MI \right) & N = \text{Odd} \end{cases}$$  \hspace{1cm} (30)

The flow chart for the calculation of switching angles is shown in Fig. 2. This technique can be extended to any number of switching angles, and the modulation index can be changed in real time.

6.1 Implementation of LM

The various steps involved in the implementation of LM are given below

**Step 1**: The required MI and number of switching angles are given to the controller.

**Step 2**: The controller generates the switching angles using Eqs. (23-30).

**Step 3**: The switching angles are compared with the carrier signal of fundamental frequency 50Hz and it is shown in Fig. 1(a).

**Step 4**: The output signals $A$ to $G$ of the comparator are used for the generation of gate pulses $S_{1a}$ to $S_{4b}$. The circuit used for the gate pulse generation is shown in Fig. 6.

**Step 5**: The generated gate pulses $S_{1a}$ to $S_{4b}$ are given to the SPMC.

7. Results and Discussions

To verify and validate the algorithms, programs are developed in MATLAB file code. The programs are run in Pentium-V computer operating at 1.4GHz clock speed. The single phase matrix converter is realized in MATLAB/Simulink environment with the following parameters $V_{inmax} = 100V$, $R = 30\Omega$, $f_{in} = 50Hz$, $f_{out} = 50Hz$.

Table 3 shows the harmonic contents of the order 3 to 13 harmonic components of the output voltage.
Real time Implementation of SHE PWM in Single Phase Matrix Converter using Linearization Method

Table 3. Comparison of THD and harmonic contents for different MI using RGA and PSO

<table>
<thead>
<tr>
<th>MI</th>
<th>Tech</th>
<th>THD</th>
<th>RMS</th>
<th>Peak</th>
<th>H3</th>
<th>H5</th>
<th>H7</th>
<th>H9</th>
<th>H11</th>
<th>H13</th>
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<tr>
<td>0.1</td>
<td>RGA</td>
<td>276.5</td>
<td>7.21</td>
<td>10.2</td>
<td>5</td>
<td>8</td>
<td>9.5</td>
<td>8.9</td>
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<td>0.3</td>
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<td></td>
<td>PSO</td>
<td>273.48</td>
<td>7.27</td>
<td>10.28</td>
<td>5.1</td>
<td>3.1</td>
<td>5.1</td>
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<td>12.28</td>
<td>20.2</td>
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<td>1.5</td>
<td>3.95</td>
<td>1.2</td>
<td>2.1</td>
<td>3.4</td>
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<tr>
<td></td>
<td>PSO</td>
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<td>14.24</td>
<td>20.13</td>
<td>0.9</td>
<td>1.05</td>
<td>1.25</td>
<td>0.55</td>
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<tr>
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<td>147.85</td>
<td>21.79</td>
<td>30.82</td>
<td>3.00</td>
<td>3.50</td>
<td>4.17</td>
<td>1.83</td>
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<td>8.70</td>
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<td>1.75</td>
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<td>1.73</td>
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<tr>
<td></td>
<td>PSO</td>
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<td>35.59</td>
<td>50.33</td>
<td>1.28</td>
<td>1.18</td>
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<td>0.22</td>
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<td>0.6</td>
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<td>74.55</td>
<td>42.61</td>
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<td>0.64</td>
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<tr>
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<td>57.24</td>
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<td>70.86</td>
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<td>0.14</td>
<td>0.31</td>
<td>0.49</td>
<td>0.47</td>
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<tr>
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<td>PSO</td>
<td>58.37</td>
<td>49.60</td>
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<td>0.31</td>
<td>0.31</td>
<td>0.17</td>
<td>0.27</td>
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</tr>
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<td>79.90</td>
<td>0.49</td>
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<td></td>
<td>PSO</td>
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Table 4. Comparison between simulation and hardware results

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<td>79.8</td>
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<td>0.3</td>
<td>28.4</td>
<td>0.41</td>
</tr>
<tr>
<td>0.2</td>
<td>18.9</td>
<td>0.63</td>
</tr>
<tr>
<td>0.1</td>
<td>8.8</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Fig. 3. Switching angle trajectory using RGA and PSO

Fig. 4. Switching angle trajectory using LM

for various modulation indices in RGA and PSO. The required fundamental voltage is obtained in both the techniques.

Fig. 5. (a) Output of the comparator in simulation for MI = 0.5; (b) Output of the comparator in hardware for MI = 0.5

The seven output signals $A$ to $G$ from the comparator in simulation and hardware are shown in Fig. 5(a) and 5(b). From these seven signals, the eight gate pulses $S_{L_e}$ to $S_{L_o}$ for the SPMC are generated using the circuit shown in Fig. 6. The gate pulses generated in simulation and hardware are shown in Fig. 7(a) and 7(b). Fig. 8 shows the harmonic spectrum using RGA and PSO for the
modulation index of 0.6. Fig. 9 and 10 show the harmonic spectrum of LM obtained for the modulation indices of 0.2, 0.4, 0.6 and 0.9 on the simulation and real time respectively. Fig. 8, 9 and Fig. 10 confirm that the fundamental voltage
is equal to the required MI and the harmonic contents H3 to H13 are minimized. Fig. 11 shows the output voltage of SPMC for MI of 0.6 using LM on simulation and hardware. Fig. 12 shows the comparison of harmonic contents measured using RGA, PSO and LM on simulation as well as real time with that of the grid code EN50160 for the modulation index of 0.6 and it is clear that the harmonic contents are less than the value specified by the grid code. Fig. 13 shows the comparison of % THD using RGA, PSO and LM. It is observed that the THDs in all the techniques are almost the same. Fig. 14 shows the experimental setup of selective harmonic elimination of single phase matrix converter. Table 4 shows the comparison of various components using LM on simulation and hardware.

The deviation in harmonic contents and fundamental voltage may be due to the fact that

Fig. 10. Harmonic Spectrum of LM for MI = 0.2, 0.4, 0.6 and 0.9 in hardware

Fig. 11. Output Voltage on simulation and hardware with MI = 0.6

Fig. 12. Comparison of Harmonic contents.

Fig. 13. Comparison of THD

Fig. 14. Experimental setup of SPMC for SHE
1) The input frequency in simulation is 50Hz. In real time, the input frequency is 49.97Hz.
2) The switching angle decimal accuracy in simulation is four digits, but in real time it is two digits.
3) The ideal switches are used in the simulation where on-state resistance of the switches is zero. But in real time, the on-state resistance of the switch leads to on-state voltage drop.

8. Conclusion

A new technique known as Linearization Method is proposed in this paper for SHE in single phase matrix converter. From the results, the following conclusions are observed at:

1) The proposed algorithm is applicable for the system in which switching losses are intolerable and can tolerate the harmonics to a certain extent. The switching frequency is the fundamental output frequency of the system.
2) In this technique, the objective function is not needed. Hence the proposed method provides an alternative to engineering optimization problems, and the optimum switching angles are derived using simple calculations.
3) The selected harmonics in LM, RGA and PSO are less than that of grid code EN50160.
4) This technique can be extended to N switching angles and it eliminates N-1 selected harmonics for all modulation indexes.
5) This technique can be readily implemented in hardware and is suitable for real time applications.

9. References

[18] Young-Doo Yoon and Seung-KiSul ‘Carrier Based Modulation Technique for Matrix Converter’, IEEE
Real time Implementation of SHE PWM in Single Phase Matrix Converter using Linearization Method


P. Subha Karuvelam She received BE and ME degree from PSG College of Technology, India and Anna University, Chennai respectively. She is currently working as Assistant Professor in Government College of Engineering, Tirunelveli, India. Her research interests include Optimization Techniques, Selective Harmonic Elimination in Power converters and Power electronics and Drive systems.

M Rajaram He received B.E and M.E degree from M.K University, Madurai and Bharathiyar University, Coimbatore, India respectively. He received his Ph.D degree from Bharathiyar University, Coimbatore, India. He is currently working as Vice-Chancellor, Anna University, Chennai. His research interests include control systems, power electronics and electrical drives.