Exploration of Modulation Index in Multi-Level Inverter Using Particle Swarm Optimization Algorithm

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Abstract

This research paper describes the Particle Swarm Optimization algorithm real with Selective Harmonic Elimination-Pulse Width Modulation (SHEPWM) method for harmonic minimization of Cascaded H-Bridge Multi-Level Inverter. In SHEPWM method-PSO algorithm is capable of determining the required switching angles to eliminate desired value of harmonics. The value of harmonics may reach up to the 11th order from the inverter output voltage waveform while keeping the magnitude of the fundamental harmonics at a certain value. Hence, the proposed method does capable of eliminating a great number of specific harmonics and the output voltage results in a minimum Total Harmonic Distortion value. The simulation results shows that the PSO algorithm successfully attains the global solution faster than other algorithms.

Keywords: Multi-level inverter; Selective harmonic elimination; Pulse width modulation; Particle Swarm Optimization (PSO); Total harmonic distortion (THD);

1. INTRODUCTION

The electrical system has major problems due to the presence of harmonic contents in the power quality features. Generally, harmonics may be classified into two types: voltage harmonics and current harmonics. Voltage harmonics and current harmonics cause huge power losses, high Electro Magnetic Interferences and pulsating torque in AC motor drives. Thus, there is a need for a new technical development to minimizes the total energy consumption, improve efficiency and enhance the power quality in all industrial and consumer applications. Current harmonics usually occurs from voltage supply and type of loads such as resistive load, capacitive load, and inductive load. Harmonics are created by neither the source nor the load side. Usage of non-linear load such as converters, computer devices, printers and etc. generate harmonics.
Magnetic cores of transformer and motors may overheat when there is load harmonics. Inverters are introduced in power conversion system and eventually it is considered as a device that plays major roles in power electronics. Various researches are carried out to improve the quality of output voltage indicated by a lower value of THD\(^1\). Multilevel inverters have been invented as the demands increases. Multi-level inverter produces a sine wave with a minimum value of THD\(^2\). Multilevel inverter is suitable for medium and high voltage application i.e. Flexible AC Transmission Systems, laminators, mills, conveyors, compressors, and industrial drive\(^3\). In general, the multi-level inverter is categorized into three types: Diode-Clamp Multi-Level Inverter (DCMLI)\(^4\), Flying Capacitor Multi-Level Inverter (FCMLI)\(^5\), and Cascaded H-Bridge Multi-Level Inverter (CHBMLI)\(^6\). Therefore, several methods like sine-triangle PWM (SPWM)\(^7\), Optimal Minimization of Total Harmonic Distortion (OMTHD)\(^8\) and Selective Harmonic Elimination Pulse Width Modulation (SHEPWM)\(^9\) are implemented for harmonic elimination in the multi-level inverter. SHEPWM is a renowned technique for switching pulses generation. This minimizes the THD from a voltage waveform generated by a voltage-source inverter (VSI)\(^10\). Normally, the Newton-Raphson method is used which is also a traditional analytical methods for solving the harmonic problem. SPWM method is very effective for observing the inverter output voltage but this method can cause high switching loss due to high switching frequency. OMTHD can only process to minimize the THD, it cannot consider the importance of lower order harmonics, higher order harmonics\(^11,12\). SHEPWM is the most effective method to eliminate low-order harmonics and subjected to low switching frequency. It improves output power quality and also reduces the cost of filter\(^13\). Some other methods like Newton-Raphson (N-R) method\(^14\), Walsh functions\(^15\) and Block-pulse functions\(^16\) are involved in the harmonic minimization process in the multi-level inverter. All these methods have its own disadvantage to solve this harmonic problem. N-R method requires initial guess, divergence problems and gives no optimum solution. Walsh function and Block-pulse function only solves linear equations, in the case of non-linear transcendental equations, are difficult to find better-switching result\(^16\). The method requires proper initial values to converge to a proper solution. Recently, non-traditional methods based on evolutionary algorithms, such as Particle Swarm Optimization (PSO)\(^17\), Bee Algorithms (BA) have been employed for inverter harmonic elimination\(^18\).

In this research, the Particle Swarm Optimization approach can be programmed in the SHEPWM method to solve the transcendental equation of switching angles. This is to make sure to find the optimal solution. The proposed method can compute the optimal solution of switching angles to eliminate the low order harmonics and minimize the THD value efficiently as compared to iterative methods and the resultant theory approach. With the proposed method, the required switching angles are computed efficiently by PSO and proposed algorithm gives the better harmonic profile of the overall inverter system.

2. CASCADED H-BRIDGE MULTI-LEVEL INVERTER

A cascaded multilevel inverter shows the advantages such as modularity layout, fewer components, the absence of extra clamping diodes or voltage balancing capacitors and the number of output voltage levels can be easily adjusted as compared to capacitor clamped and diode clamped multilevel inverter. In CHBMLI, the period of switches turn ON and OFF process can be done in only once per cycle. Therefore, it simply solves the switching loss problem. Fig. 1 shows the CHBMLI have series of H-bridge (single-phase full-bridge) inverter units. Each full-inverter bridge produces three different voltage outputs: \(+V_{dc}\), 0, and \(-V_{dc}\). However, CHBMLI produces staircase output voltage waveform. Therefore, the voltage level of CHBMLI is measured in \(2S + 1\), where \(S\) is the number of DC sources. The output voltage waveform of a 7-level CHBMLI with three isolated dc sources (\(S = 3\)).

3. SELECTIVE HARMONIC ELIMINATION PULSE WIDTH MODULATION METHOD

The SHEPWM method used for the proposed PSO algorithm to calculate the switching strategy. SHEPWM is also the most famous switching strategy that is widely used to specifically eliminate the selected order harmonics from the output waveform of the inverter. CHBMLI produces output phase voltage with suitable switching angles. Initially, harmonics are in the output phase voltage. Furthermore, odd harmonics are difficult to calculate although the even
harmonics is zero at the output phase voltage. Hence, SHEPWM method can use Fourier analysis function calculate the odd harmonics in the phase voltage. Accordingly, Fourier analysis of output phase voltage is given by

$$V(\omega t) = \sum_{n=1}^{\infty} V_n \cos(n\omega t) + V_n \sin(n\omega t)$$

(1)

Considering the output voltage and amplitude of dc sources would be written as:

$$V(\omega t) = \sum_{n=1}^{\infty} V_n \sin(n\omega t)$$

(2)

Where $V_n$ is the amplitude and voltage waveform of $n^{th}$ harmonic component. In SHEPWM method, switching angles can be limited to zero and $\pi/2$. Consequently $V_n$ develops to describe the odd and even function is given as,

$$V_n = \frac{4}{n\pi} V_{dc} \sum_{i=1}^{n} \cos(n\alpha_i), n=\text{odd and } V_n = 0, n=\text{even.}$$

In this paper, SHEPWM can be implemented to eliminate 3rd, 5th and 7th harmonics. Similarly, low order harmonics can be determined by solving the transcendental non-linear equation of switching angles are provided as follows,

$$V_n = \frac{4}{n\pi} V_{dc}(a_1) + V_{dc}(a_2) + V_{dc}(a_3)$$

(3)

$$V_5 = \frac{4}{5\pi} V_{dc}(5a_1) + V_{dc}(5a_2) + V_{dc}(5a_3)$$

(4)

$$V_7 = \frac{4}{7\pi} V_{dc}(7a_1) + V_{dc}(7a_2) + V_{dc}(7a_3)$$

(5)

Equations (4) and (5) are set to zero to eliminate fifth and seventh harmonics respectively. Modulation index to represent the fundamental voltage of $V_1$ is given as

$$M = \frac{V_1}{sV_{DC}}$$

(6)
Substituting equation (3), (4), (5) into (6) to get nonlinear equation (7) can be followed:

\[
M = \frac{4}{3\pi} \cos(a_1) + \cos(a_2) + \cos(a_3)
\]

\[
0 = \cos(5a_1) + \cos(5a_2) + \cos(5a_3)
\]

\[
0 = \cos(7a_1) + \cos(7a_2) + \cos(7a_3)
\]  \hspace{1cm} (7)

Now optimal switching angles can be named as \(a_1\), \(a_2\), and \(a_3\) that found depend on modulation index. Thus, PSO algorithm can be programmed for finding the optimal switching value for eliminating lower order harmonics and maintained their fundamental voltage value.

4. PARTICLE SWARM OPTIMIZATION ALGORITHM

In 1995, Kennedy and Eberhart presented PSO which is an investigative method. Essentially, PSO was enthused by the sociological behavior of food searching criteria such as a group of birds and fish manner. PSO is an effective and fastest optimization algorithm for finding the optimal solution of the nonlinear problems. In PSO, the particle has to be considered as an initial value to find the finest solution for the optimization problem. In the basic particle swarm optimization algorithm, particle swarm consists of \(n\)th particles, and the position of each particle stands for the potential solution in \(D\)-dimensional space. The particles change its condition according to the following three principles:

- To possess its inertia value,
- To change the condition depend on its most optimist position and velocity,
- To change the condition depend on its swarm’s most optimist position and velocity.

In PSO, optimal solution depends upon \(G_{best}\) and \(P_{best}\). \(G_{best}\) known as global and \(P_{best}\) known as personnel best. Every time particles can be updated to define the possible solution with respect to position and velocity vectors. Position vectors said to be \(X_i = [x_1, x_2, ..., x_D]\) and the velocity vector \(V_i = [v_1, v_2, ..., v_D]^{13}\) when entering search space where each particle can expand the search criteria depend on the present best value, previous best value, and experience of neighboring best value. Equations (8) and (9) modify the particles with respect to velocity and position vectors. Generally, position and velocity value can be updated using the following condition,

\[
p = p + v
\]  \hspace{1cm} (8)

\[
v = v + c_1 \ast \text{rand} \ast (P_{best} - p) + c_2 \ast \text{rand} \ast (G_{best} - p)
\]  \hspace{1cm} (9)

Therefore the velocity and position equation is given as

\[
V_{id}^{k+1} = V_{id}^k + c_1 r_1 (p_{best_{id}}^k - x_{id}^k) + c_2 r_2 (g_{best_{id}}^k - x_{id}^k)
\]  \hspace{1cm} (10)

\[
X_{id}^{k+1} = X_{id}^k + V_{id}^{k+1}
\]  \hspace{1cm} (11)

where \(c_1\) and \(c_2\) are the constraints of cogitative and social task respectively. Meanwhile, \(r_1\) and \(r_2\) are random values for the initial solution of PSO and its range is within 0 to 1. In PSO, to assume \(\theta_i = [\theta_1, \theta_2, ..., \theta_s]\) be a trial vector representing the particle of the entered swarm to be established.

Step 1: Set the population value with proper locations and range of velocities.
Step 2: Assessment the fitness of the individual particle in the entire swarm(PBest).
Step 3: Analyse the fitness of individual global particles in the entire swarm (GBest).
Step 4: Adjust PBest and GBest Position based on updating velocity constraints
Step 5: Update the particles position at the end of every iteration.
Step 6: Terminate the iteration process if the condition can get Optimal value
Step 7: Go to Step 2.
Start

Initialize the random population for switching angle

Enter the range of iteration count and velocity value

Satisfying the nonlinear constraints based on pseudo code

Evaluate the $G_{\text{best}}$ and $P_{\text{best}}$ value in the entire swarm and Update the particle in the every iteration

Estimate the optimal switching angle and Update the $G_{\text{best}}$ and $P_{\text{best}}$ value

Is optimum Criteria reached?

Yes

Select the best optimal solution on the iteration process

End

Fig. 2. The flow chart for PSO algorithm.

Above statements show all the steps used to calculate the optimal value. A flow chart in Fig. 2 describes the process that gone through. It shows the quantity of optimal switching angles for eliminating the lower order harmonic and minimizing the THD valve.

5. SIMULATION RESULTS

The SHEPWM method is programmed by PSO algorithm using MATLAB/Simulink system. These SHEPWM together with 11-level CHBMLI is used later on. In proposed SHEPWM method, PSO algorithm has been used to find the optimal solution for calculating the required switching angles. Therefore PSO program can be written in a m-file editorial in MATLAB tool box. The no. of levels, maximum iteration, no.of. switching angels and modulation index are initialized in PSO program. Table. 1 presents the block parameter for the PSO algorithm.

The PSO program can be developed by using if-else statement and for loop condition. Fig. 3 shows the estimation of fitness value in switching pulse strategy between 1 to 3 by using PSO. The estimation of fitness value in switching pulse strategy between 4 to 6 is shown in Fig. 4. Fig. 5 depicts the estimation of fitness value in switching pulse strategy between 7 to 9 estimation. Fig. 6 shows the estimation of fitness value switching pulse strategy between 10 to 12.
Table 1. Program Parameter of PSO Algorithm.

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Name of the Block</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Sources</td>
<td>05</td>
</tr>
<tr>
<td>2.</td>
<td>Levels</td>
<td>11</td>
</tr>
<tr>
<td>3.</td>
<td>Voltage</td>
<td>Value 100 V</td>
</tr>
<tr>
<td>4.</td>
<td>Modulation Index</td>
<td>0.1-1</td>
</tr>
<tr>
<td>5.</td>
<td>Max Iteration</td>
<td>1000</td>
</tr>
<tr>
<td>6.</td>
<td>Initialize Population</td>
<td>300</td>
</tr>
<tr>
<td>7.</td>
<td>Voltage Magnitude</td>
<td>0.02</td>
</tr>
<tr>
<td>8.</td>
<td>Size of Modulation Index</td>
<td>10</td>
</tr>
<tr>
<td>9.</td>
<td>Required Frequency</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

Fig. 3. Switching pulse strategy of 1 to 3.

Fig. 4. Switching pulse strategy of 4 to 6.

Fig. 5. Switching pulse strategy of 7 to 9.

Fig. 7 shows the harmonic order for the given output phase voltage of CHBMLI using PSO. The output pulse voltage of CHBMLI for the given Modulation Index= 0.8 and Load Phase Angle=120 degree is shown in Fig. 8.
Fig. 6. Switching pulse strategy of 10 to 12.

Fig. 7. Harmonic Order Vs Magnitude-Phase Output Voltage.

Fig. 8. Output Phase Voltage of MI=0.8 at Load Phase Angle = 120 degree

Fig. 9 depicts the harmonic order for the given output phase voltage of CHBMLI using PSO. Fig. 10 shows the output pulse voltage of CHBMLI for the given Modulation Index = 0.9 and Load Phase Angle=120 degree.

Fig. 9. Harmonic Order Vs Magnitude-Phase Output Voltage.
Table 2 shows that the simulation result of PSO algorithm in SHEPWM method, it shows RMS voltage and THD value for the various modulation index values.

<table>
<thead>
<tr>
<th>Modulation Index</th>
<th>RMS output voltage ($V_{oRMS}$)</th>
<th>RMS value of output voltage fundamental component</th>
<th>$%V_{oRMS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>40.8855</td>
<td>16.7162</td>
<td>22.2</td>
</tr>
<tr>
<td>0.3</td>
<td>50.2887</td>
<td>25.2896</td>
<td>17.8</td>
</tr>
<tr>
<td>0.4</td>
<td>58.1488</td>
<td>33.8128</td>
<td>13.9</td>
</tr>
<tr>
<td>0.5</td>
<td>65.1517</td>
<td>42.4474</td>
<td>11.4</td>
</tr>
<tr>
<td>0.6</td>
<td>71.1688</td>
<td>50.6500</td>
<td>9.80</td>
</tr>
<tr>
<td>0.7</td>
<td>76.7500</td>
<td>58.9139</td>
<td>8.30</td>
</tr>
<tr>
<td>0.8</td>
<td>82.1900</td>
<td>67.5671</td>
<td>6.98</td>
</tr>
<tr>
<td>0.9</td>
<td>87.4450</td>
<td>766.4662</td>
<td>5.57</td>
</tr>
</tbody>
</table>
Fig. 11 demonstrates the comparison of THD value with various modulation index. In this part, THD value comes in 5% at modulation index $= 0.9$. THD value is very low in the proposed method (THD = 5.5%). In the proposed method, lower order harmonics are eliminated.

6. CONCLUSION

In this paper, PSO algorithm is used in SHEPWM scheme and solve the non-linear problem by Simulation. The proposed SHEPWM method is used to solve a non-linear transcendental equation to find optimum switching angle for CHBMLI. The simulation results are provided for an 11-level CHBMLI to validate the accuracy of the computational results. The PSO-based algorithm is determined with a high-precision set of solutions. These solutions are of switching angles with a relatively high-speed convergence and these develop the power quality of the system.

References