AN EVOLUTIONARY BASED SELECTIVE HARMONIC ELIMINATION METHOD SUITABLE FOR HIGH POWER CONSTANT FREQUENCY CONVERTERS USED IN RENEWABLE ENERGY SOURCES

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Abstract

Ever increasing power crisis, rapid depletion of fossil fuels and the pollution (due to power generation) forces engineering community to look for a green power by exploiting the renewable energy sources such as solar or wind power generation. Harnessing electrical energy from renewable sources is feasible if suitable high power converters/inverters are designed. However the high power converters/inverters introduce harmonics in the power grid as well as in the source. This proposed work addressed the problem of solving selective harmonic elimination pulse width modulation (SHE-PWM) for high power multilevel inverters in constant frequency utility grid. The big issues in solving the nonlinear transcendental equations are, it has multiple optimal solutions, the convergence and the initial guess of the exact solution is an uphill task. This paper devised two evolutionary algorithms, the Real coded Genetic Algorithm (RGA) and differential evolution algorithm (DE) which results in reducing computational difficulties while the convergence is too fast. An objective function was formulated in such a way that it eliminates the selective harmonics effectively while controlling the fundamental component and it reduces the total harmonic distortion (THD) for different operating points. The theoretical calculations were verified using the simulation results and it was observed that DE results are far more superior to GA.

Keywords: SHE-PWM-selective harmonic elimination-pulse width modulation; RGA-real coded genetic algorithm.

1. Introduction

Of late, multilevel inverters have received increased attention due to its modularity
and their higher capacity voltage operation, high efficiency and low electromagnetic interference (EMI) [1]. The sources of multilevel inverters are batteries, photovoltaic arrays, fuel cells, rectifiers. Several dc voltages are used to synthesize any desired level of output voltage in multilevel inverter which in-turn reduces switching losses, and also results lower voltage stress across the switches. By increasing the number of levels in a given topology, the output voltages have more steps generating a staircase waveform, which approaches closely the desired sinusoidal waveform and also offers reduced harmonic distortion [1-3]. The main challenges of varying voltage steps are to determine switching angles for the staircase modulation. The switching angles as well as the variations of voltage steps determine the harmonic distortion of output voltage [4-7].

The multilevel selective harmonic elimination, the multilevel space vector control, the optimal-combination modulation, and the staircase modulation are low switching frequency schemes [3, 8]. The staircase modulation is very popular, particularly for the cascade multilevel inverters. Methods that work with high switching frequencies have many switching in one period of the fundamental output voltage. In recent years, SHE-PWM techniques have received more and more attention because of their advantages over other modulation methods, including acceptable performance with low switching frequency to fundamental frequency ratios, direct control over output waveform harmonics, and the ability to cancel triplen harmonics in three phase systems [9].

SHE-PWM can be expanded into Fourier series which is a highly non-linear equation. These non-linear transcendental equations contain trigonometric terms, solving which provide multiple sets of solutions [3-5]. Many algorithms have been proposed in the technical literature to deal with the problem of finding the desired solutions, which can be categorized into two sets [5, 10].

The iterative Newton–Raphson (N–R) method belongs to the first [3]. The disadvantage of iterative methods is their dependence on an initial guess and divergence problems are likely to occur for large number of inverter levels. Also, they can only find one set of solutions.
The second group include elimination theory, Walsh functions, optimization techniques such as particle swarm optimization (PSO) and genetic algorithms (GA) [3-5] which introduces optimum angles so that the equations are minimized. They are free from derivation. Agelidis et al. [4] investigated multicarrier-based SPWM method in comparison with the multilevel SHE-PWM method and concluded that the SHE-PWM method offers significantly higher converter bandwidth than the multicarrier-based SPWM method and also reduces switching frequency with the similar waveform quality in the full range of modulation index.

Photo voltaic (PV) based multilevel inverter for single phase grid connected system is getting more attention since it generates pollution free green energy. In recent years, the state-of-the-art technology is the two-level multi-string converter. This converter consists of several PV strings that are connected with dc–dc converters to a common dc–ac converter.

This paper is organized as follows. Section 2 explains about the problem formulation. GA is presented in section 3. Then, the DE algorithm is explained in Section 4. Section 5 shows the simulation and experimental results that validate the proper operation of the inverter.

### 2. Problem Formulation

The phase voltage waveform for an 11-level cascaded H-bridge inverter requires five separate dc sources (SDCs) and five full bridges as shown in Fig. 1 and its corresponding waveform in Fig. 2. The number of output phase voltage levels ‘\(m\)’ in a cascade inverter is defined by \(m = 2p + 1\), where ‘\(p\)’ is the number of separate dc sources.

By applying Fourier series analysis, the staircase output voltage of multilevel inverters with unequal sources can be described as follows:

\[
V(t) = \sum_{n=1,3,5,\ldots}^{m} \frac{4V_{dc}}{n\pi} \times (k_1 \cos(n\Phi_1) + k_2 \cos(n\Phi_2) + \ldots + k_p \cos(n\Phi_p))
\]  

(1)

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**Fig. 1.** Photovoltaic cascaded multilevel inverter.

**Fig. 2.** Voltage waveform of multilevel inverter.
Switching angles $\Phi_1-\Phi_p$ must satisfy the following condition:

$$0 \leq \Phi_1 \leq \Phi_2 \leq . . . \leq \Phi_p \leq \frac{\pi}{2}$$

(2)

The control of the multilevel inverter is to choose a series of switching angles $\Phi_1, \Phi_2, \ldots, \Phi_p$ such that the total harmonic distortion is minimum for a desired sinusoidal voltage waveform as well as predominant low frequency harmonics, 5th, 7th, 11th, and 13th, are eliminated. $p-1$ number of harmonics can be eliminated from the output voltage of the inverter. To eliminate the fifth-order harmonic for a five-level inverter, the expression given below must be satisfied.

$$k_1 \cos(\Phi_1) + k_2 \cos(\Phi_2) = (\pi/2)M$$

(3)

$$k_1 \cos(5\Phi_1) + k_2 \cos(5\Phi_2) = 0$$

(4)

where, ‘$M$’ is Modulation index defined as $M = V_1/ pV_{dc}$ and $V_1$ is the fundamental voltage. The THD is calculated using the following formula:

$$THD = \sqrt{\sum_{n=1}^{15} \frac{V_n^2}{V_1^2}}$$

(5)

In this paper it is proposed that, the switching angles of multilevel inverter are determined using genetic algorithms (GA) and differential evolutionary algorithm (DE) and the results are compared.

3. Genetic Algorithms

Genetic algorithms (GAs) are simple, powerful, general purpose, derivative free, stochastic global search algorithm [6]. Genetic algorithms are gradient free, so they do not need functional derivative information to search for a set of solutions that minimize (or maximize) a given objective function. The GA’s important properties such as reproduction, crossover, mutation, reduce the computational burden and search time and also enable them to solve complex objective functions [11]. This paper presents genetic algorithms based selective harmonic elimination for an eleven level inverter.

Procedure of solving SHE using GA

The following steps are considered:

**Step 1.** Generate a population of initial solution of $\Phi_1, \Phi_2, \ldots, \Phi_p$:

Initialize population size and range of firing angles. Check the constraint.

**Step 2.** Evaluation of objective function:

Substitute the initial values of $\Phi_1, \Phi_2, \ldots, \Phi_p$ to evaluate harmonic components using Eqs. (1) and (3) together with average output voltage for initial population.

**Step 3.** Evaluation of fitness function:
Each particle is evaluated using the fitness function of the harmonic minimization problem.

The switching angles $\Phi_1$, $\Phi_2$, ..., $\Phi_p$ are minimized using the cost function:

$$f(\Phi_1, \Phi_2, ..., \Phi_p) = 100$$  \hspace{1cm} (6)

**Step 4.** Generation of offspring:

To produce $N_p$ offspring from parents use selection, crossover, and mutation. In this work roulette wheel selection is used. The crossover and mutation is then performed on the remaining chromosomes.

**Step 5.** Current populations are replaced by new populations.

**Step 6.** Go to Step 2.

### 4. Differential Evolution (DE) Algorithm

Differential Evolution, the DE algorithm was introduced by Storn and Price in 1995 [12]. It is similar to the structure of EAs (Evolutionary Algorithms), but its generation of new candidate solutions and its use of a 'greedy' selection scheme differ from conventional EAs [12]. The good convergence properties and its simplicity to use made the DE algorithm more popular for many practical problems. The experimental results showed that DE was far more efficient and robust (with respect to reproducing the results in several runs) compared to PSO and the EA.

The following are the steps in DE:

**Step 1.** Generate randomly a population of $N_p$ vectors, each of $n$ dimensions:

$$D_{i,j} = D_{\text{min}, j} + \text{rand}(0,1) \times (D_{\text{max}, j} - D_{\text{min}, j})$$  \hspace{1cm} (7)

where $D_{\text{min}, j}$ and $D_{\text{max}, j}$ are lower and upper bounds for $j^{th}$ component respectively, rand(0,1) is a uniform random number between 0 and 1.

**Step 2.** Calculate the objective function value $f(D_i)$ for all $D_i$.

**Step 3.** Select three points from population and generate perturbed individual $W_i$:

$$W_i^{(G)} = D_{\text{best}}^{(G)} + F(D_{\text{best}}^{(G-1)} - D_{\text{best}}^{(G-1)})$$  \hspace{1cm} (8)

**Step 4.** Recombine the each target vector $D_i$ with perturbed individual generated in Step 3 to generate a trial vector $U_i$.

**Step 5.** Check whether each variable of the trial vector is within range. If yes, then go to Step 6, else make it within range using $U_{ij} = 2 \times D_{\text{min}, j} - U_{ij}$, if $U_{ij} < D_{\text{min}, j}$ and $U_{ij} = 2 \times D_{\text{max}, j} - D_{ij}$, if $U_{ij} > D_{\text{max}, j}$ and go to Step 6.

**Step 6.** Calculate the objective function value for vector $U_i$.

**Step 7.** Choose better of the two for next generation.
Step 8. Check whether convergence criterion is met if yes then stops; otherwise go to Step 3.

5. Simulation Results and Discussion

The switching angles determined using GA algorithm for different modulation scheme is given in Table 1. It was obvious that as the modulation level increases the THD level decreases significantly. Figs. 3 to 5 give the results of an eleven level inverter. The output phase voltage for different modulation indices ‘M’ is given in Fig. 3(a) M=0.47, Fig. 4(a) M=0.7 and Fig. 5(a) M=1.07. Their corresponding FFT analysis is given in Fig. 3(b) M=0.47, Fig. 4(b) M=0.7 and Fig. 5(b) M=1.07.

<table>
<thead>
<tr>
<th>M</th>
<th>Φ_1</th>
<th>Φ_2</th>
<th>Φ_3</th>
<th>Φ_4</th>
<th>Φ_5</th>
<th>Best fitness value</th>
<th>THD</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.47</td>
<td>37.6770</td>
<td>52.9404</td>
<td>67.9967</td>
<td>87.2381</td>
<td>88.4476</td>
<td>2.6361</td>
<td>3.635</td>
</tr>
<tr>
<td>0.7</td>
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<td>45.1437</td>
<td>52.7554</td>
<td>67.0311</td>
<td>73.9256</td>
<td>1.8798</td>
<td>2.979</td>
</tr>
<tr>
<td>1.075</td>
<td>4.5004</td>
<td>12.0497</td>
<td>21.3627</td>
<td>29.8443</td>
<td>44.9095</td>
<td>1.3775</td>
<td>2.414</td>
</tr>
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</table>

Similarly the switching angles for DE algorithm and THD values for different modulation scheme are given in Table 2. There was not much difference in THD level for both algorithm for M=0.47, M=0.7 but it decreased slightly for M=1.07 for DE algorithm. The phase voltage for the different harmonic order using DE algorithm was far better than GA results. It is obvious from the Fig. 3(b) the third harmonic magnitude was 20 volts, the peak magnitude of fundamental component was around 50 volts for modulation index M=0.47. There was a negligibly small magnitude of 9^{th}, 15^{th}, 21^{th}, 23^{th} appears in Fig. 3(b). As discussed earlier there is no need to bother about the triplen harmonics. However for modulation index M=0.7 third order harmonics is 25 volts but all other harmonics was zero except 15^{th} order which was also a triplen harmonics. In Fig. 5(b) the FFT analysis for modulation index M=1.07 was given in which the peak magnitude was around 110 volts and except the third order harmonic all other harmonics was closer to zero.

<table>
<thead>
<tr>
<th>M</th>
<th>Φ_1</th>
<th>Φ_2</th>
<th>Φ_3</th>
<th>Φ_4</th>
<th>Φ_5</th>
<th>Best fitness value</th>
<th>THD</th>
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<td>49.2436</td>
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<td>72.4167</td>
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<td>6.9998</td>
<td>8.3367</td>
<td>21.9034</td>
<td>27.9978</td>
<td>42.9525</td>
<td>0.9428</td>
<td>2.404</td>
</tr>
</tbody>
</table>
Fig. 3. (a) Output phase voltage for $M = 0.47$, (b) Corresponding FFT analysis for $M = 0.47$.

Fig. 4. (a) Output phase voltage for $M = 0$, (b) Corresponding FFT analysis for $M = 0.7$.

Fig. 5. (a) Output phase voltage for $M = 1.07$, (b) Corresponding FFT analysis for $M = 1.07$. 
6. Conclusions

This paper has used the evolutionary based algorithm GA and DE for solving nonlinear transcendental equation for finding switching angles for an eleven level inverter in such a way that the lower order harmonics 5th, 7th, 9th, 11th, 13th are removed. As the modulation index increased there was an improvement in the peak magnitude of fundamental component voltage and also the improvement in reduction of 9th, 15th, 21st, 23rd order harmonics. The modulation index M=1.07 except 3rd harmonics all other harmonics were closer to zero. The DE algorithm was far superior than GA while solving the problem with reduced time with low THD. The results have been verified using Matlab version 7.10, in Intel /i3/2.20Ghz speed, 2GB ram machine. This method was very robust for photo voltaic application in the sense that the SDCs can be replaced by a string of PV panels.

References
