Photovoltaic inverters optimisation

C. R. Sanchez Reinoso[a,b,c*], M. De Paula[d], D. H. Milone[a], R. H. Buitrago[b]

[a]Research Center for Signals, Systems and Computational Intelligence, UNL; Ciudad Universitaria UNL, Santa Fe 3000, Argentine
[b]Institute of Technology Development for the Chemical Industry (INTEC), CONICET; Guemes 3450, Santa Fe 3000, Argentine
[c]Center for Design and Optimisation of Systems (DOS), UNCa.; Maximio Victoria 55, Catamarca 4700, Argentine.
[d]Institute of Development and Design (INGAR), CONICET; Avellaneda 3657, Santa Fe 3000, Argentine.

Abstract

Multilevel inverters are widely used in solar energy generation systems consist of various photovoltaic generators. These converters deliver distorted output waveforms. There are trascendental equations characterizing the harmonic content but the degree of the polynomial increases with the number of DC sources or the number of harmonics to be eliminated. Also, the solutions are discontinuous in some points.

In this paper, a way is proposed to minimize the output harmonics of a multilevel inverter, especially those of lower order. The Particle Swarm Optimization algorithm used to minimize the Total Harmonic Distortion, subject to restrictions on the harmonic content allowed. The appropriate switching angles can be calculated to eliminate low order harmonics.

The proposed method has been succesfully applied to a cascaded multilevel converter of seven levels. Then, this method can be extended to more levels inverters. In case of a real-time application, the method can be useful because the switching angles can be stored.

Keywords: Photovoltaic; converters, optimisation.

1. Introduction

Photovoltaic solar energy is one of the most widely used renewable energy. A key component in photovoltaic generation systems is the DC-AC converter [1,2]. In these applications multilevel inverters are usually used. These can give an AC voltage from several DC sources, that is, from the photovoltaic generators. Multilevel inverters have lower output harmonic content monolevel inverters.

There are different methods in order to eliminate harmonic distortion [3,4]. But these methods only remove low-order harmonics efficiently.

There are trascendental equations characterizing the harmonic content [5] and the problem can be converted to polynomial equations that can be solved using the resultant theory. The degree of the

polynomial increases with the number of DC sources or the number of harmonics to be eliminated. Therefore, more complex expressions are obtained by increasing the size of the problem and the time required to calculate the optimal switching angles. Some ways to reduce the computational cost are proposed [6,7] but the solutions are discontinuous in some points, causing problems to find the switching angles possible at those points. In addition, the are many number of switching required to eliminate high order harmonics, causing great switching losses.

In this paper, a way is proposed to minimize the output harmonics of a multilevel inverter, especially those of lower order. The Particle Swarm Optimization algorithm (PSO) [8] is used to minimize the Total Harmonic Distortion (THD), subject to restrictions on the harmonic content allowed. The appropriate switching angles can be calculated to eliminate low order harmonics.

The optimal THD is calculated for different modulation indexes eliminating selected order harmonics and the problems of discontinuity in the solution of the nonlinear function.

The proposed method is also capable of finding all possible sets of solutions of nonlinear equations. This can be useful in a real-time application.

A background on cascade multilevel inverters is given below. Then, in section 3 the particle swarm optimization method is described briefly. Section 4 shows the results and the final section summarizes the work conclusions.

2. Cascade multilevel inverter

The cascade multilevel inverter is one of the most important topologies in multilevel inverters. This requires less number of components compared to other topologies and does not need specially designed transformers. In addition, this topology occupies less space and can be employed a simple switching control [9,10]. The cascade multilevel inverter consists of the series connection of several monolevel inverters H-bridge type with their respective DC power supplies. Each H-bridge can produce three different voltages, by connecting the DC sources to AC side through different switching activation sequences. The H-bridges are connected in series, obtaining the multilevel converter output by adding the monolevel converters outputs. The output voltage is given by [11].

$$v_{an}(\omega t) = \sum_{k=1,3,5}^{\infty} \frac{4V_{dc}}{k\pi} \cos(k\alpha_1) + \cos(k\alpha_2) + \cos(k\alpha_3) \sin(k\omega t) \tag{1}$$

where *s* is the number of cascaded H bridge by phase. The number of levels in the output voltage is *2s+1*, where, s is the number of H-bridges per phase.

To obtain the desired peak fundamental voltage V_f, is required to determine switching angles such that

$$0 < \alpha_1 < \alpha_2 < \alpha_3 < \frac{\pi}{2} \tag{2}$$

and that some low-order harmonics of phase voltage are zero. With regard to the switching angles.

Usually a switching angle is used to select the fundamental voltage. The remaining *s-1* switching angles are used to eliminate certain lower order harmonics. In the three phase power systems, triplen harmonics are automatically canceled in the output line voltage. Therefore, only non triplen odd harmonics are present in the output line voltage [12].

From (1), the expression for the fundamental voltage in terms of switching angles is given by

$$V_f = \frac{4V_{dc}}{\pi}\left(\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3)\right) \tag{3}$$

When all the switching angles are zero, the maximum fundamental voltage is obtained as $\max(V_f) = 4sV_{dc} / \pi$. The relationship between the fundamental and the maximum voltage available is given by the modulation index. The modulation index m is defined as the ratio between the output fundamental voltage and the maximum achievable fundamental voltage. Therefore, the expression for m is [11].

$$m = \frac{\pi V_f}{4sV_{dc}} \tag{4}$$

For a cascade multilevel inverter of seven levels, there are three H-bridges per phase. One freedom degree is used to control the magnitude of fundamental voltage. Harmonics 5th and 7th are the most ones that contribute to harmonic distortion [12] and are eliminated using the two remaining freedom degrees.

The equations for selective harmonics elimination can be written as following

$$c_1 = \frac{4}{\pi}\left[1 + 2\sum_{k=1}^{m}\left(-1^k\right)\cos(\alpha_k)\right] = M \tag{5}$$

sinc(*i*) Research Center for Signals, Systems and Computational Intelligence (fich.unl.edu.ar/sinc)
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$$c_5 = \frac{4}{5\pi}\left[1 + 2\sum_{k=1}^{m}\left(-1^k\right)\cos\left(5\alpha_k\right)\right] = 0 \tag{6}$$

$$c_7 = \frac{4}{7\pi}\left[1 + 2\sum_{k=1}^{m}\left(-1^k\right)\cos\left(7\alpha_k\right)\right] = 0 \tag{7}$$

3. Particle swarm optimisation

PSO is an optimization method, based on an biologic type model, that has solved problems in different areas [13,14,15]. It is a based population optimization technique inspired by social behavior of bird flocking or fish schooling. The algorithm defines the number of particles or agents into the solution space as starting solution. Then, each particle randomly moves over the space, and in each iteration every particle records its best position (pb). Futhermore, the best position of all the particles (gb) is stored. In this next iteration, this information is used by every particle to decide where to move. The velocity is updated according to the next expression

$$v_i(n+1) = wv_i(n) + a_1 r_1\left(pb_i - p_i(n)\right) + a_2 r_2\left(gb_i - p_i(n)\right) \tag{8}$$

where $v_i(n)$ is the velocity of particle i at iteration n; $p_i(n)$ is the position of particle i at iteration n; w is the inertia weight; a_1 and a_2 are acceleration coefficients that define the influence of the personal and the group experiences respectively; r_1 and r_2 are two independent random sequences uniformally distributed in [0,1]. After a number of iterations, the particles will eventually cluster around the area where the fittest solutions are. The new particle local position that allows to explore the search space is

$$p_i(n+1) = p_i(n) + v_i(n) \tag{9}$$

4. Proposed method

First, it is considered the total harmonic distortion (THD) expression

$$THD = \sqrt{\frac{1}{c_1}\sum_{n=3}^{\infty}\left(c_n\right)^2}\,100 \tag{10}$$

where $n = 6i \pm 1 \, (i = 1,2,3,...)$

The selective harmonic elimination problem is formulated as an optimization problem. The objective function is THD. The restrictions are (2) and the individual harmonics do not exceed the limit imposed.

This allows to eliminate the complexity of finding the solution for the nonlinear trascendental equations of the SHE problem. The pseudocode of proposed method is

begin

Random values for $\underline{\alpha}$ and $\underline{v}$

repeat

repeat

Compute $\underline{\alpha}$

Compute $F(\underline{\alpha})$

Compute minimization $F(\underline{\alpha})$ subject to restrictions

until not satisfied $0 < \alpha_1 < \alpha_2 < \alpha_3 < \frac{\pi}{2}$ for each population

Find *pb* and *gb* for $\underline{\alpha}$

Compute new $\underline{\alpha}$ using $\underline{v}$, and find *pb* and *gb*

until *pb=gb* for each generation

end

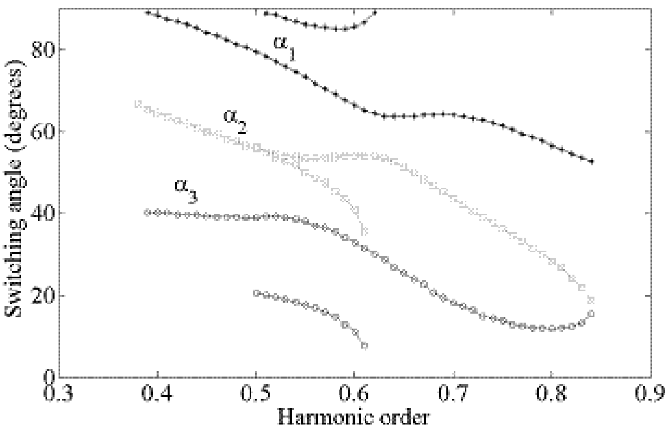

Fig. 1. Switching angles for different modulation indexes.

5. Results

In this work, the THD (10) is used to evaluate the performance of the multilevel inverter.

The goal is to find the optimum vector for the employed modulation index.

The parameters were set r to 0.8, a to 1.6 and w_0 to 7.

The optimum switching angles for a seven levels inverter are shown in Fig. 1. It is important to note that the proposed minimization method finds all sets of solutions.

According to the simulation results, for certain modulation indexes, several sets of solutions are available. Fig. 1 shows the switching angles for different modulation indexes. The solutions only includes angles that result in zero 5th and 7th order harmonics.

Fig. 2 shows the first 50 harmonics for M=0.6 when the proposed technique is applied. From Fourier Transform Analysis it is clear that the 5th and 7th order harmonics have been totally eliminated. The triplen harmonics are present due to the fact that the synthesized waveform is a single phase one.

The proposed method has been succesfully applied to a seven levels cascaded inverter.

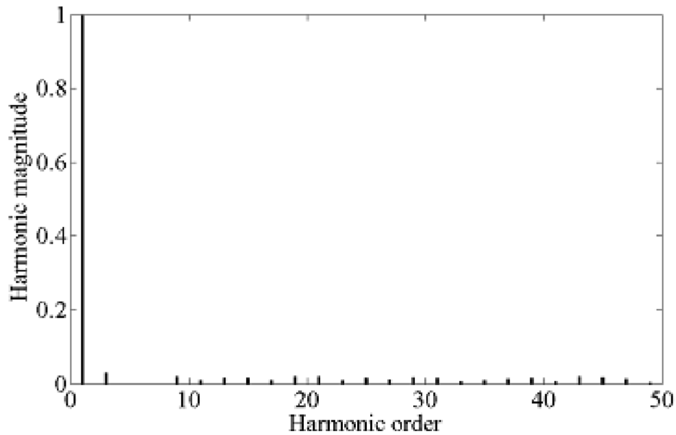

Fig. 2. Harmonics Switching angles for different modulation indexes.

6. Conclusions

In this paper, a way is proposed to minimize the output harmonics of a multilevel inverter, especially those of lower order. The PSO algorithm is used to minimize the THD, subject to restrictions on the harmonic content allowed. The appropriate switching angles can be calculated to eliminate low order harmonics. The optimal THD is calculated for different modulation indexes eliminating selected order harmonics and the problems of discontinuity in the solution of the nonlinear function. The proposed method is also capable of finding all possible sets of solutions of nonlinear equations.

The results show that proposed approach for the harmonic optimization of multilevel inverters works properly. This method was applied to the seven levels cascaded multilevel inverters. Then, this method can be extended to more levels inverters.

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