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An application of PSO technique for harmonic elimination in a PWM inverter☆

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ABSTRACT

Harmonic elimination problem in PWM inverter is treated as an optimization problem and solved using particle swarm optimization (PSO) technique. The derived equation for computation of total harmonic distortion (THD) of the output voltage of PWM inverter is used as the objective function in the PSO algorithm. The objective function is minimized to contribute the minimum THD in the voltage waveform and the corresponding switching angles are computed. The method is applied to investigate the switching patterns of both unipolar and bipolar case. While minimizing the objective function, the individual selected harmonics like 5th, 7th, 11th and 13th can be controlled within the allowable limits by incorporating the constraints in the PSO algorithm. The results of the unipolar case using five switching angles are compared with that of a recently reported work and it is observed that the proposed method is effective in reducing the voltage THD in a wide range of modulation index. The simulated results are also validated through suitable experiments.

1. Introduction

In PWM based inverters, generally the harmonic elimination problem is formulated as a set of nonlinear transcendental equations that must be solved to determine the switching angles so as to produce desired fundamental amplitude while eliminating selected harmonics [1–3]. The fundamental component is assigned a desired output value and the other selected orders of harmonics are equated to zero to form the set of transcendental equations. By solving these equations, switching angles are computed to eliminate specifically selected harmonics. The technique is simple in principle but not so simple to solve the equations as they have multiple solutions. Moreover, the solutions may have discontinuity at certain modulation indices. Challenging approaches have been reported by several papers [4–11] which try to modify its numerical process of solution. The technique has found to have multiple solutions and this fact deepens its numerical aspects. The Walsh function method has been reported to simplify the process [5–7]. In the application of SHE technique, generally the PWM switching angles are calculated off line and subsequently stored into lookup tables. However with a large number of possibilities of modulation index and the required interpolation, the computing requirement can be quite substantial. This drawback has motivated researchers to look for methods that will allow the switching angles to be computed online; thus avoiding the need for large memory storage. An online computation method has been proposed to make the technique a more flexible and interactive one by using neural networks [8]. Using sine wave approximation approach a set of non-transcendental equations is derived to compute near optimal harmonic elimination PWM angles [9]. Prediction of initial values allows rapid convergence of Newton iteration for the solution of nonlinear equations [10]. In Ref. [11], homotopy based computation technique is used to find all possible solutions of SHE problem for the bipolar switching pattern. A different method using the mathematical theory of resultants is proposed to find a third set of solution in addition to the existing two sets of solution by the conventional methods [12]. Another scheme for online calculation of PWM angles has been proposed by Salam [13], which is based on the quadratic curve fitting of trajectories of the exact PWM angles. Multiple solutions to the SHE problem are found in Ref. [14] and harmonics are minimized through an objective function by optimization [15]. Any number of specific higher order harmonics of multilevel converter can be eliminated by the method as proposed in Ref. [16]. Very recently a modified carrier waveform approach is suggested by Wells et al. [17]. The method is based on modulation rather than solution of nonlinear equations or numerical optimization. However, most of the methods need an initial guess of the variables on which the convergence towards the actual solution is dependent. The initial guess, if not properly considered, the number of iterations may either increase substantially or the solution may not converge at all in some cases.

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A new class of search and optimization technique has become very popular in many engineering applications. These methods search from a population of points instead of a single point as in conventional search and optimization techniques. Moreover they do not require a suitable initial guess. The initial points need to be randomly generated from the search space. Though these methods have extensively been used in many engineering applications, their applications are very limited in the design of power electronic circuits. For example, a differential evolution (DE) algorithm is used to solve the SHE-PWM problem with constraint that any two consecutive solutions are well separated [18]. Genetic algorithms (GA) can be used to speed up the solution of SHE problem as proposed in Refs. [19,20]. Particle swarm optimization (PSO) is one such evolutionary technique that was discovered through simulation of a simplified social model viz. bird flocking, fish schooling, etc. [21], and presently being used in many applications for optimization of nonlinear equations. PSO is very simple in organization and has only three control parameters, viz. inertia weight and constriction factors. On many applications PSO has been reported to have better performance than GA or DE [22,23]. Moreover PSO is capable of producing the optimum solution with a very small population size.

In this paper, a method based on PSO technique is proposed to minimize the THD of the output voltage of PWM inverter. The objective function derived from the SHE problem is minimized using PSO algorithm to compute the switching angles without going for the multiple solutions of the set of nonlinear equations. In the present approach, the PSO algorithm searches for all possible set of solutions to contribute the minimum THD, as considerable number of generations with a large number of populations in each generation is incorporated within the algorithm. In the proposed PSO algorithm, as the variables are randomized initially, the initial guess does not affect the actual solution. The present approach searches for possible minimum THD at all modulation indices, thus the problem of discontinuity of solutions at certain points is avoided. The method is found to be effective in both unipolar and bipolar switching cases. The proposed method is experimentally verified by storing the angles computed through simulation, in a micro-controller for both unipolar and bipolar cases with three and five switching angles. The experimental values of THD and individual harmonic amplitudes conform to the simulated ones.

This paper is organized as follows. The proposed scheme is described in Section 2. Section 3 depicts some simulation results of unipolar and bipolar cases using different number of switching angles. Experimental results are presented in Section 4 and finally conclusion is drawn in Section 5.

2. The proposed scheme

2.1. Harmonic elimination principle

A typical output voltage waveform of a PWM inverter as shown in Fig. 1 contains harmonics and the output function $f(t)$ can be expressed in Fourier series as

$$f(t) = \sum_{n=1}^{\infty}(a_n \sin n\alpha_n + b_n \cos n\alpha_n) \quad (1)$$

Due to quarter wave symmetry of the output voltage, the even harmonics are absent and only odd harmonics are present [24]. The amplitude of the n-th harmonic a_n is expressed only with the first quadrant switching angles $\alpha_1, \alpha_2, \ldots, \alpha_m$:

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

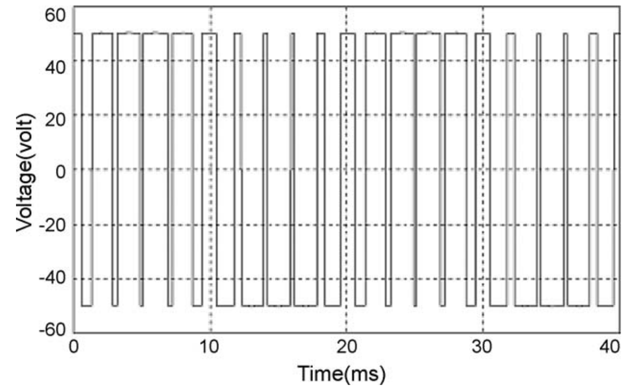

Fig. 1. Output waveform of a bipolar PWM inverter.

and

$$0 < \alpha_1 < \alpha_2 < \ldots \alpha_m < \left(\frac{\pi}{2}\right) \quad (3)$$

For any odd harmonics, (2) can be expanded up to the k-th term where m is the no. of variables corresponding to switching angles α_1 through α_m of the first quadrant.

In selected harmonic elimination, α_n is assigned the desired value for fundamental component and equated to zero for the harmonics to be eliminated:

$$\begin{aligned}
a_1 &= \left(\frac{4}{\pi}\right)\left[1 + 2\sum_{k=1}^{m}(-1)^k \cos \alpha_k\right] = M \\
a_5 &= \left(\frac{4}{5\pi}\right)\left[1 + 2\sum_{k=1}^{m}(-1)^k \cos 5\alpha_k\right] = 0 \\
&\vdots \\
a_n &= \left(\frac{4}{n\pi}\right)\left[1 + 2\sum_{k=1}^{m}(-1)^k \cos n\alpha_k\right] = 0
\end{aligned} \quad (4)$$

where M is the amplitude of the fundamental component.

Nonlinear transcendental equations are thus formed and after solving these equations, α_1 through α_k are computed. Triplen harmonics are eliminated in three phase balanced system and these are not considered in Eq. (4). It is evident that $(m-1)$ harmonics can be eliminated with m no. of switching angles.

2.2. Proposed PSO method

The principal limitation with the application of conventional PWM SHE technique has been the analytical difficulty in solving the nonlinear equations. These equations contain trigonometric terms, are transcendental in nature and therefore exhibit multiple solutions. To obtain convergence with numerical techniques, the initial values of the variables must be selected considerably close to the exact solution. In the proposed PSO method, the complexity of finding the solution of these nonlinear equations is avoided by converting the SHE problem to an optimization problem. The %THD of the output voltage can be computed using (5):

$$\%THD = \left[\frac{1}{a_1^2}\sum_{n=5}^{\infty}(a_n)^2\right]^{1/2} \times 100 \quad (5)$$

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

The same expression of THD of the output voltage is considered as the objective function $F(\alpha)$ that has to be minimized with the constraints of selected harmonic elimination. Mathematically the problem can be formulated as follows: