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A PSO based optimal switching technique for voltage harmonic reduction of multilevel inverter

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ABSTRACT

Selected lower order harmonics of multilevel inverter are eliminated while the overall voltage THD is optimized by computing the switching angles using particle swarm optimization (PSO) technique. The discontinuity in the solution of selected harmonic elimination (SHE) problem at certain modulation indices is avoided by optimizing the individual harmonics to allowable limits. While choosing the set of solution leading to minimum THD, the abrupt changes in the switching angles are discarded by limiting the voltage THD within allowable limits. Also the selected higher order harmonics are eliminated by additional switching along with the lower order harmonics. In order to reduce the computational burden for online application, the switching angles computed by the proposed PSO technique for optimum THD at varying modulation indices are stored as a look-up table in the DSP memory. The simulated results are also validated through suitable experiments.

1. Introduction

A multilevel inverter is useful for high power application at higher voltage level by connecting different dc sources of lower voltage level (Menzies, Steimer, & Steinke, 1994; Tolbert, Peng, & Habetler, 1999). The desired ac voltage is synthesized from several dc sources by cascading individual inverters (Lai & Peng, 1996). Multilevel inverters can be used to interconnect several distributed generations (DG) like solar, fuel cell, rectified output of wind energy with the ac grid. However, the main concern is eliminating the harmonics from the output voltage of multilevel inverter. The output voltage of the inverter must meet maximum THD limitations as specified in Duffey and Stratford, 1989. There are several methods used for harmonic elimination. Traditional SHE PWM method is widely used (Carrara, Gardella, Marchesoni, Salutari, & Sciutto, 1992; Enjeti, Ziogas, & Lindsay, 1990; Hammond, 1997; Loh, Holmes, & Lipo, 2005). Carrier based PWM technique is also reported (Tolbert & Habetler, 1999; Holmes & McGrath, 2001). But with these methods, higher order harmonics of the output voltage are not completely eliminated though the lower order harmonics are efficiently eliminated. To address the problem of higher order harmonics, an active harmonic elimination technique (Du, Tolbert, & Chiasson, 2006) has been proposed. In this method, the resultant theory (Chiasson, Tolbert, Mckenzie, & Du, 2003) is first applied to transcendental equations characterizing the harmonic contents to eliminate low order harmonics like 5th, 7th, 11th and 13th and to determine switching angles for the fundamental frequency switching. Next, the residual higher order harmonics are eliminated by generating a square wave (one for each of these harmonics) with additional switching angles whose fundamental is the opposite of the harmonic that is to be eliminated. Though the method is effective, the required number of switching is substantially high for the elimination of increased higher order harmonics. Moreover, at certain points of modulation indices, there are discontinuities in the solution. In Jiang and Lipo (2000) the dc link voltage of the multilevel inverter is optimized while a genetic algorithm is used for harmonic optimization in Ozpineci, Tolbert, and Chiasson (2004).

Previously reported work (Chiasson et al., 2003) shows that the transcendental equations characterizing the SHE problem can be converted into polynomial equations that can be solved using the resultant theory. Further as degree of polynomials increases with the number of dc sources or order of harmonics to be eliminated, the theory of symmetric polynomials (Chiasson, Tolbert, Mckenzie, & Du, 2005) is exploited to reduce the degree of polynomial equations that can reduce the computational burden. With reduced degree of polynomials, an online computation method for the switching angles has been proposed with all multiple solutions. But since the solutions are having discontinuity at certain points (Chiasson et al., 2005; Du et al., 2006), it is difficult for the controller to generate possible switching angles at those points. Moreover,

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the additional switchings required to eliminate higher order harmonics will be considerably high causing high switching losses.

In this paper, a PSO (Kennedy & Eberhart, 1995) based technique is suggested to minimize the overall THD of the output voltage of a multilevel inverter. The objective function derived from the SHE problem is minimized using PSO algorithm, to compute the switching angles while lower order harmonics are eliminated. Besides eliminating lower order harmonics, the selected higher order harmonics are optimized to contribute minimum voltage THD by using additional switching angles. Since in the proposed method, the optimum THD is computed at different modulation indices eliminating selected order of harmonics, the problem of discontinuity in solution of nonlinear function is avoided. But at certain points, the computed switching angles leading to minimum voltage THD shows abrupt variations. At those points, a small compromise between additional voltage THD and linearisation of switching angles is made to facilitate online application. The proposed method is also capable of finding all possible sets of solution of the nonlinear equations (Chiasson, Tolbert, Mckenzie, & Du, 2004). The combinations of switching angles corresponding to minimum voltage THD at sufficiently close points of modulation indices with consideration of linearity between two successive points are stored in a DSP memory for online application.

2. Harmonic elimination technique

A higher level ac voltage can be synthesized by cascading several lower level inverters supplied from equal or unequal dc sources. This configuration is known as multilevel configuration of inverters. A single-phase structure of a cascade multilevel inverter is shown in Fig. 1. In case of equal dc sources $V_{dc1} = V_{dc2} \ldots = V_{dcn} = V_{dc}$. The synthesized ac output voltage waveform is the sum of all the individual inverter outputs. The number of output phase voltage levels of cascade multilevel inverter is $2N + 1$, where N is the number of dc sources. An output voltage waveform of a 7-level cascade multilevel inverter with three dc sources is shown in Fig. 2.

2.1. Conventional method

The output voltage waveform $V(t)$ of the multilevel inverter as shown in Fig. 2 can be represented by (1)

$$V(t) = \sum_{n=1}^{\infty} (an \sin n\alpha_n + bn \cos n\alpha_n) \tag{1}$$

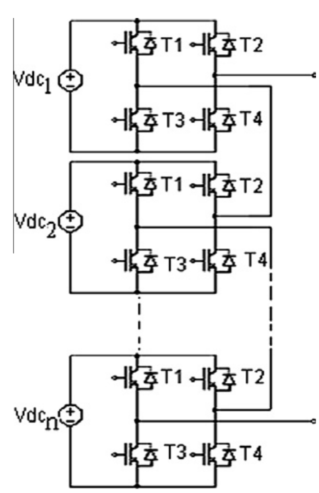

Fig. 1. Single-phase configuration of a multilevel inverter.

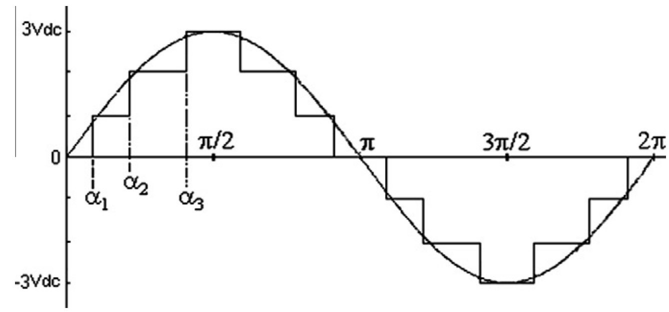

Fig. 2. Output voltage waveform of a 7-level multilevel inverter.

The even harmonics are absent ($bn = 0$) due to quarter wave symmetry of the output voltage (Mohan, Undeland, & Robbins, 2003). The n-th harmonic an is expressed with the first quadrant switching angles $\alpha_1, \alpha_2, \ldots \alpha_m$.

$$an = (4V_{dc}/n\pi) \sum_{k=1}^{m} \cos(n\alpha_k) \tag{2}$$

and

$$0 < \alpha_1 < \alpha_2 < \ldots \alpha_m < (\pi/2) \tag{3}$$

For any odd harmonics, (2) can be expanded up to the k-th term where m is the number of variables corresponding to switching angles α_1 through α_m of the first quadrant.In selected harmonic elimination, an is assigned the desired value for fundamental component and equated to zero for the harmonics to be eliminated (Holmes & Lipo, 2003).

$$\begin{aligned} a1 &= (4V_{dc}/\pi) \sum_{k=1}^{m} \cos \alpha_k = M \\ a5 &= (4V_{dc}/5\pi) \sum_{k=1}^{m} \cos 5\alpha_k = 0 \\ &\vdots \\ an &= (4V_{dc}/n\pi) \sum_{k=1}^{m} \cos(n\alpha_k) = 0 \end{aligned} \tag{4}$$

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 (4). It is evident that $(m - 1)$ harmonics can be eliminated with m number of switching angles. These nonlinear equations show multiple solutions and the main difficulty is its discontinuity at certain points where no set of solution is available (Chiasson et al., 2003, 2004). This limitation is addressed in the present method to ease the online application at these points of discontinuity.

2.2. Proposed PSO method

The PSO methodology is a very powerful tool for optimization of nonlinear functions. The method was discovered through simulation of a simplified social model viz. bird flocking, fish schooling, etc. (Kennedy & Eberhart, 1995) and presently being used in many applications for optimization of nonlinear equations. The simplified PSO approach is as follows:

The variables of the objective function are randomized first. By iterations, the *pbest* (present best) and *gbest* (global best) values of the variables are computed. The velocity vector VX for variable $X$is then computed using the formula