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A hybrid real coded genetic algorithm – Pattern search approach for selective harmonic elimination of PWM AC/AC voltage controller

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ABSTRACT

Selective harmonic elimination-pulse width modulation techniques offer a tight control of the harmonic spectrum of a given voltage waveform generated by a power electronic converter along with a low number of switching transitions. Traditional optimization methods suffer from various drawbacks, such as prolonged and tedious computational steps and convergence to local optima; thus, the more the number of harmonics to be eliminated, the larger the computational complexity and time. This paper presents a novel method for output voltage harmonic elimination and voltage control of PWM AC/AC voltage converters using the principle of hybrid Real-Coded Genetic Algorithm-Pattern Search (RGA-PS) method. RGA is the primary optimizer exploiting its global search capabilities, PS is then employed to fine tune the best solution provided by RGA in each evolution. The proposed method enables linear control of the fundamental component of the output voltage and complete elimination of its harmonic contents up to a specified order. Theoretical studies have been carried out to show the effectiveness and robustness of the proposed method of selective harmonic elimination. Theoretical results are validated through simulation studies using PSIM software package. Finally, these results are verified by means of an experimental prototype.

1. Introduction

Medium and large power converter in motor drives, AC/AC converters, huge UPS systems, and high power flexible alternate current transmission systems (FACTSs) need switching elements which can bear high voltage/current. To overcome limits of semiconductor switches, several new techniques and topologies have been developed [1–3], such as multiple switching elements in one leg of an inverter, multiple rectifiers for unity power factor correction, optimization of motor performance indices such as harmonic current, torque ripple [4–6].

AC/AC line-commutated phase-angle control or integral cycle control with thyristor technology have been widely used. However, those techniques have many drawbacks, the retardation of the firing angle causes a lagging power factor at the input side, plentiful low order harmonics in both of supply voltages/currents and a discontinuity of power flow to the load appears [7].

Line-commutated AC/AC controllers can be replaced by pulse width modulation (PWM) AC/AC controllers using forced commutated devices, which have better overall performance and the above problems, can be improved by modifying of the power circuit with freewheeling path. PWM AC/AC voltage controllers using forced commutated devices have important advantages as compared with line-commutated AC/AC controllers with thyristors technology. These advantages include sinusoidal input–output current/voltage waveforms, does not require bulky and costly LC input/output filter components, improved input power factor, better transient response and significant reduction in the harmonic contents [8–11].

On the other hand, control by switching is often accompanied by extra losses due to the switching losses. Therefore, the reduction in the number of switching instants is essential for efficiency. Therefore, selective harmonic elimination/control has been a widely researched alternative to traditional pulse-width modulation techniques.

The selective harmonic elimination (SHE) PWM based methods can theoretically provide the highest quality output among all the PWM methods. SHE has been a research topic since the early 1960s, first examined in [12] and developed into a mature form in [13–15] during the 1970s. SHE offers several advantages compared to traditional modulation methods [16] including acceptable performance with low switching frequency to fundamental frequency ratios, direct control over output waveform harmonics, and the ability to leave triplen harmonics uncontrolled to take advantage of circuit topology in three phase systems. These key

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advantages make SHE a viable alternative to other methods of modulation in applications such as variable speed drives [17–21], or dual-frequency induction heating [22]. This method is sometimes called a programmed PWM technique. However, the drawback of these methods is a heavy computational burden and a complicated hardware [15]. The main challenge of solving the associated nonlinear equations, which are transcendental in nature and therefore have multiple solutions, is the convergence.

In this paper, a SHE-PWM model of an AC/AC voltage converters is developed that can be used for arbitrary number of switching angles. The paper proposes an efficient optimization technique called the hybrid Genetic Algorithm-Pattern Search (RGA-PS) method that reduces significantly the computational burden resulting in fast convergence. The feasibility and effectiveness of the proposed algorithm is evaluated with intensive simulation studies Simulation results for a 3 and 5 switching instants single-phase AC/AC voltage converters are presented. The paper is organized in the following manner. The basic principle of operation and problem formulation is presented in Section 2. Section 3 introduces an over view of GA and GA-PS algorithm. Description of numerical and simulation results of the SHE-PWM AC/AC voltage converters is introduced in Section 4. Section 5 presents experimental verification of the proposed selective harmonic elimination technique. Conclusions are given in Section 5.

2. Principle of operation and problem formulation

Fig. 1 shows the power circuit configuration of single-phase PWM AC/AC voltage converter, which is composed of two bi-directional power switches, one connected in series and the other in parallel with the load. The series-connected switch S1 regulates the power delivered to the load, and the parallel one S2 provides a freewheeling path to discharge the stored energy when the series one is turned off. Standard AC/AC converters require bi-directional switches. Theoretically, the switching must be instantaneous and simultaneous and alternate current path has to be provided. For practical realizations, the finite switching times and delays in the drive circuits and controlled switches have been taken into account. The firing angles are generated by a microprocessor, which generates supply-synchronized pulses from a look up table.

When a switching function shown in Fig. 2a, is applied to the single-phase AC/AC PWM voltage controller, the output voltage appears in the PWM form at the load terminals. The switch S1 is turned on at various switching angles $\alpha_1, \alpha_3, \ldots, \alpha_{M-1}$ and turned off at $\alpha_2, \alpha_4, \ldots, \alpha_M$ per quarter cycle.

Fig. 2b shows the idealized output voltage waveform of the AC/AC voltage controller, where the quarter-wave symmetry is preserved which will null the even harmonics, as will be shown. By the proper choice of PWM switching angles, the fundamental component can be controlled and a selected low order harmonics can be eliminated. Owing to the PWM waveform characteristics of odd function symmetry and half wave symmetry, even harmonics are absent and only odd harmonics exist.

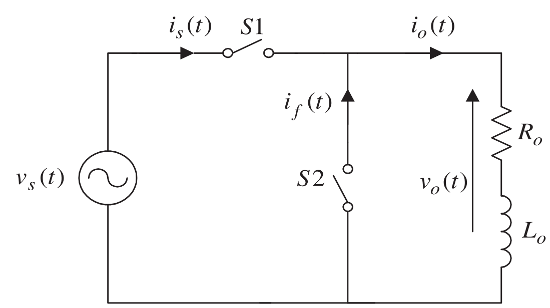

Fig. 1. PWM AC/AC voltage converter with bi-directional switches.

The Fourier series expressions for the output voltage, which are expressed in terms of the M switching point variables, can be easily express as follows:

$$v_o = \sum_{n=1}^{\infty} A_n \sin(nwt) + B_n \cos(nwt) \tag{1}$$

where $B_n = 0$ for $n = 1, 2, 3, \ldots$ and thus the above equation reduces to:

$$v_o = \sum_{n=1,3,5,\ldots}^{\infty} A_n \sin(nwt) \tag{2}$$

The value of A_n is computed as:

$$A_n = \frac{2V_m}{\pi} \sum_{i=1}^{M} (-1)^i \left[\frac{\sin(n-1)\alpha_i}{(n-1)} - \frac{\sin(n+1)\alpha_i}{(n+1)} \right] \tag{3}$$

where $n = 3, 5, \ldots, 2M-1$, M is the number of switching angles per quarter cycle, α_i is the ith switching angles and V_m is the maximum value of the input voltage. The fundamental component is given by:

$$A_1 = \left(1 + \frac{2}{\pi}\right) V_m \sum_{n=3,5,\ldots}^{\infty} (-1)^i \left[\alpha_i - \frac{\sin 2\alpha_i}{2} \right] \tag{4}$$

Consider for example, an output voltage of AC/AC converter with $M = 5$ pulses per quarter cycle as in the case of Fig. 2a. The magnitudes of the harmonic components including the fundamental are computed as:

$$\begin{aligned} A_1 = &\left(1 + \frac{2}{\pi}\right) V_m \left[-\alpha_1 + \frac{\sin 2\alpha_1}{2} + \alpha_2 - \frac{\sin 2\alpha_2}{2} - \alpha_3 + \frac{\sin 2\alpha_3}{2} \right. \\ &\left. + \alpha_4 - \frac{\sin 2\alpha_4}{2} - \alpha_5 \right] \end{aligned} \tag{5}$$

$$A_n = \frac{2V_m}{\pi} \begin{bmatrix} -\frac{\sin(n-1)\alpha_1}{(n-1)} + \frac{\sin(n+1)\alpha_1}{(n+1)} + \frac{\sin(n-1)\alpha_2}{(n-1)} - \frac{\sin(n+1)\alpha_2}{(n+1)} \\ -\frac{\sin(n-1)\alpha_3}{(n-1)} + \frac{\sin(n+1)\alpha_3}{(n+1)} + \frac{\sin(n-1)\alpha_4}{(n-1)} - \frac{\sin(n+1)\alpha_4}{(n+1)} \\ -\frac{\sin(n-1)\alpha_5}{(n-1)} \end{bmatrix} \tag{6}$$

Setting up M switching angles per-quarter cycle allows the elimination of $(M-1)$ low-order harmonics and the remaining angle is used to control the fundamental component of the output voltage. In addition, the constraints for required output fundamental voltage and elimination of harmonics up to $M-1$ order, yields M equations. Solution of theses equations enables the derivation of the required PWM switching pattern for the AC/AC voltage converter and the exact switching instants can be determined from the solutions of nonlinear harmonic equation developed above.

The problem objective is to find the switching instants such that $A_1 = V_m^*$ and to perform SHE to a specified order where V_m^* is the maximum value of the reference output voltage. In order to proceed with the optimization/minimization, an objective function describing a measure of effectiveness of eliminating selected order of harmonics while maintaining the fundamental at a pre-specified value must be defined. This is converted to an optimization problem subject to constraints. Let $F(\alpha)$ be the objective function, which it will be minimized and is defined as

$$\begin{aligned} F(\alpha) &= F(\alpha_1, \alpha_2, \ldots, \alpha_M) \\ &= (A_1 - V_m)^2 + A_3^2 + A_5^2 + \ldots + A_{M-1}^2 \end{aligned} \tag{7}$$

The correct solution must satisfy the condition

$$0 \leqslant \alpha_1 \leqslant \alpha_2 \leqslant \ldots \alpha_{M-1} \leqslant \alpha_M \leqslant \frac{\pi}{2} \tag{8}$$

The task is to determine the firing instants such that objective function $F(\alpha)$ subject to the constraint of (6) is minimized. Therefore, the output voltage is regulated ideally over the full range