Simulated Anealing Algorithm Based Optimization for Cascaded Multilevel Inverters

G. Sugumaran, L. Vinothkumar, A. Isvariya, M. Janardhanan

Abstract—This project presents the SA optimization method for harmonic elimination in a cascaded multilevel inverter. The main objective in selective harmonic elimination pulse width modulation strategy is eliminating low-order harmonics by solving nonlinear equations, while the fundamental component is satisfied. In this paper, the simulated annealing algorithm (SA) is applied to a 9-level inverter for solving the equations. The algorithm is based on the cooling of a high temperature metal behavior under fast cooling constraint. This method has higher precision and probability of convergence than the genetic algorithm (BA). MATLAB software is used for optimization and comparison of BA and SA. Simulation results are expected to show superiority of SA over BA in attaining accurate global minima and higher convergence rate. Also, its performance is almost 10 times lesser time for running.

I. INTRODUCTION

Today, there are many applications for multilevel inverters, such as flexible ac transmission system (FACTS) equipment [1], high voltage direct current lines [2], and electrical drives [3]. There are three conventional structures for multilevel inverters: diode-clamped [4], flying capacitor [5], and cascaded multilevel inverter with separate dc sources [1]. For improving inverter performance and output quality, different methods have been suggested. The first of them is using various switching strategies, such as sinusoidal or “subharmonic” natural pulse width modulation (SPWM), selective harmonic elimination PWM (SHEPWM), space-vector modulation (SVM), optimized harmonic-stepped waveform (OHSW) [7], [8], and optimal minimization of THD (OMTHD) [9]. The second method is using a low-pass filter in the output of inverters to eliminate high-order harmonics. Finally, the third approach is using multilevel structures in order to reduce harmonics and THD. The SHEPWM strategy has also been used in multilevel inverters. In this method, the objective is elimination of low-order harmonics, while the fundamental harmonic is satisfied. If this goal cannot be obtained, the highest possible harmonics optimization is desired. In this approach, by solving $S$ equations, $(S-1)$ low-order harmonics from the fifth order can be eliminated and the fundamental component is satisfied. Solving SHEPWM nonlinear equations is a major problem in obtaining switching angles. So far, several methods have been suggested which can be categorized into two sets. The first group is based on satisfying the equations. The Newton–Raphson (N–R) method is one of these [10]. The disadvantage of iterative methods is their dependence upon an initial guess and divergence problems likely to occur for large numbers of inverter levels. Also, they can only find one set of solutions. In addition, using the MATLAB function Solve, all roots can be obtained based on the Gauss–Newton method [11]. A mathematical method based on theory of resultant is proposed in [12]. This method can only find all possible solutions for those feasible Modulation index $M$ solutions that exist. However, it is complicated and time-consuming and requires new expression when voltage level or input dc voltage is changed. Also, the Homotopy algorithm [13] is used to determine one set of solutions. Since the first group does not suggest any optimum solutions for infeasible $M$, the second group of methods has been applied based on evolutionary algorithms. These methods can not only find solutions, where low-order harmonics can be completely eliminated, but they can also find solutions for infeasible $M$; the second group introduces optimum angles so that these equations are minimized. These methods are simple and can be

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Cascaded multilevel inverter with separate dc source
used for problems with any number of levels. They are free from derivation. GA is one of the methods that have been used in the literature [14], [15]. In addition, particle swarm optimization [7], bacterial foraging algorithm [16], and ant colony [17] methods have been introduced. GA is widely used and is simpler and more applicable. In this paper, the bee algorithm (BA) is applied to minimize low-order harmonics, as well as to satisfy the desired fundamental component. Results including the probability of reaching to a global solution and the effect of running times are compared with those obtained by GA. Results confirm the effectiveness of the proposed algorithm and its superiority over GA. Experimental results are presented to confirm the simulation results.

II. MULTILEVEL INVERTERS

A. Multilevel Inverter Topology

A cascaded multilevel inverter (see Fig. 1) has advantages that have been presented in [18]. Few components, the absence of extra clamping diodes or voltage balancing capacitors, and easy adjustment of the number of output voltage levels are some of them. Switching devices turn ON and OFF only once per cycle to overcome the switching loss problem. The cascaded multilevel inverter consists of a series of H-bridge (single-phase full-bridge) inverter units. Each full-bridge can generate three different voltage outputs: +Vdc, 0, and −Vdc. However, all three multilevel inverters can produce staircase waveform as shown in Fig. 2. The number of output phase voltage levels in a cascaded multilevel inverter is 2S + 1, where S is the number of dc sources. For example, phase voltage waveform for a 7-level cascaded multilevel inverter with three isolated dc sources (S = 3) is shown in Fig. 2. Each H-bridge unit generates a quasi-square waveform by phase-shifting the switching timings of its positive and negative phase legs.

B. Selective Harmonic Elimination PWM

A 7-level inverter waveform shown in Fig. 2 has three variables θ1, θ2, and θ3, where Vdc1, Vdc2, and Vdc3 are assumed to be equal. Considering equal amplitude of all dc sources, the Fourier series expansion of the output voltage waveform, shown in Fig. 1, will be written as $V(\omega t) = \sum_{n=1}^{\infty} V_n \cos(n\theta_i)$, where $V_n$ is the amplitude of the nth harmonic. Switching angles are limited between zero and $\pi/2$ ($0 \leq \theta_i < \pi/2$). Because of odd quarter-wave symmetric characteristic, harmonics with even order become zero. Consequently, $V_n$ becomes

$$V_n = \begin{cases} \frac{4V_{dc}}{\pi} \sum_{i=1}^{S} \cos(n\theta_i) & \text{for odd } nS \\ 0 & \text{for even } nS \end{cases}$$

The objective of SHEPWM is to eliminate the lower order harmonics while remaining harmonics are removed with filter. In this paper, without loss of generality, a 7-level inverter is chosen as a case study to eliminate its low-order harmonics (fifth and seventh). It is needless to take the triplen harmonics into consideration since they will vanish in three-phase applications. So, to satisfy fundamental harmonic and eliminate fifth and seventh harmonics, three nonlinear equations with three angles are provided

$$V_1 = \frac{4V_{dc}}{\pi} \left[ \cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) \right]$$
$$V_5 = \frac{4V_{dc}}{5\pi} \left[ \cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) \right]$$
$$V_7 = \frac{4V_{dc}}{7\pi} \left[ \cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) \right]$$

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$$V_7 = \frac{4V_{dc}}{7\pi} \left[ \cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) \right].$$

(3)

$$M \geq \frac{V_1}{12V_{dc}/\pi} \quad (0 \leq M \leq 1).$$

Here, M is between 0 and 1 to cover different values of $V_1$.

Thus, by substituting (4) into (3), (5) can be derived and for a 7-level inverter the goal is to solve the following set of equations

$$M = \frac{1}{3} \left[ \cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) \right]$$
$$0 = \cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3)$$
$$0 = \cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3).$$

Now, three switching angles, namely $\theta_1$, $\theta_2$, and $\theta_3$, must be found with respect to the range of $M$.

III. SA ALGORITHM

$x = 10^{-7}$ is selected to be more reliable. For all run numbers, the CDF of BA is more than the CDF of GA. So, SA has better performance for finding solutions.
IV. EXPERIMENTAL RESULT

For verifying BA solutions, a 3-phase 2-kW hardware prototype 7-level inverter as shown in Figure. It consists of three full-bridge inverters that are connected in a series form. DC source voltage of each H-bridge inverter is constant and is selected to be 12V. Also, the frequency of the output is assumed to be 50 Hz.

Switching angles are obtained offline by SA for the range of M. The angles are loaded in an 89s52 microcontroller a lookup table. For each M, 89s52 findswitching angles from the lookup table. 89s52 transfersthe switching signals to optocoupler 6N137 for isolation of insulatedgate bipolar transistor (IGBT) from 89s52. Finally, the signal is transmitted to IGBT driver 7667 that is connected to IGBT and supplies Qge that is required for turning IGBT ON. Figure shows the output phase voltage for M = 0.8. Switching angles are shown in Table III. According to this point feasible. The data in Fig. 13 are extracted from the Tektronix TDS1002B oscilloscope and related frequency spectrum is plotted with FFT analysis of the Simulink/Powergui block. Fig. 14 which shows the frequency spectrum confirms the results. Fig. 15 shows the output line voltage. Fig. 16 shows the frequency spectrum of this waveform. Low-order harmonics as well as triple harmonics are removed.

V. CONCLUSION

In this paper, elimination of low-order harmonics using SHEPWM strategy is investigated. SA is applied to solve the equation. Simulation results show accuracy and ability of SA for convergence objectives. Also, solutions have near probability to attain global minimum for 1, 2, 5, and 10 times runs and this probability is higher than the same runs for GA. Finally, to verify SA solutions, experimental results are presented which validate the accuracy of the proposed method.

REFERENCES