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Simulated Anealing Algorithm Based Optimization for Cascaded Multilevel Inverters

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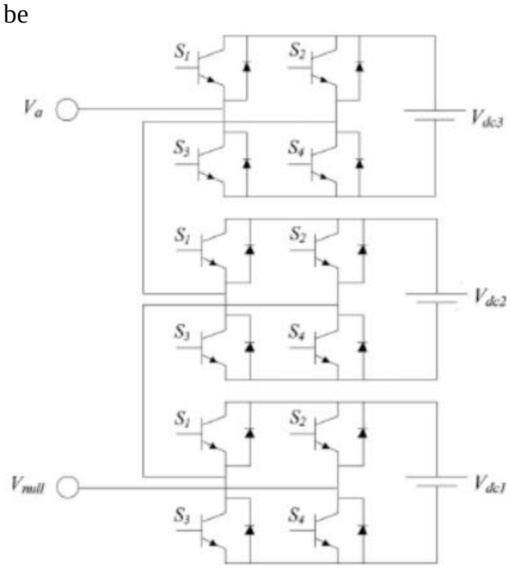
Abstract— This project presents the SA optimization method for harmonic elimination in a cascaded multilevel inverter. The main objective in selective harmonic elimination pulse width modulation strategy is eliminating low-order harmonics by solving nonlinear equations, while the fundamental component 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 electricaldrives [3]. There are three conventional structures for multilevelinverters: diode-clamped [4], flying capacitor [5], andcascaded multilevel inverter with separate dc sources []. Forimproving inverter performance and output quality, differentmethods have been suggested. The first of them is using variousswitching strategies, such as sinusoidal or "subharmonic" naturalpulsewidth modulation (SPWM), selective harmonic eliminationPWM(SHEPWM), space-vector modulation (SVM), optimizedharmonic-stepped waveform (OHSW) [7], [8], and optimalminimization of THD (OMTHD) [9]. The second methodis using a low-pass filter in the output of inverters to eliminatehigh-order harmonics. Finally, the third approach is using multilevelstructures in order to reduce harmonics and THD. TheSHEPWM 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 goalcannot be obtained, the highest possible harmonics optimization s desired. In this approach, by solving S equations, $(S-1)$ loworderharmonics from the fifth order can be eliminated and thefundamental component is satisfied. Solving SHEPWM nonlinearequations is a major problem in obtaining switching angles.So far, several methods have been suggested which can be categorizedinto two sets. The first group is based on satisfyingthe equations. The Newton–Raphson (N–R) method is one ofthese [10]. The disadvantage of iterative methods is their dependenceon an initial guess and divergence problems are likely tooccur for large numbers of inverter levels. Also, they can onlyfind one set of solutions. In addition, using the MATLAB function

Solve, all roots can be obtained based on the Gauss–Newtonmethod [11].A mathematical method based on theory of resultant is proposedin [12]. This method can only find all possible solutionsfor those feasible Modulation index$M$ solutions that exist. However,it is complicated and time-consuming and requires newexpression when voltage level or input dc voltage is changed.Also, the Homotopy algorithm [13] is used to determine one setof solutions.Since the first group does not suggest any optimum solutionsfor infeasible M, the second group of methods have been appliedbased on evolutionary algorithms. These methods can notonly find solutions, where low-order harmonics can be completelyeliminated, but they can also find solutions for infeasible$M$; the second group introduces optimum angles so that theequations are minimized. These methods are simple and can be



Cascaded multilevel inverter with separate dc source

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used for problems with any number of levels. They are free fromderivation. GA is one of the methods that have been used in theliterature [14], [15]. In addition, particle swarm optimization [7],bacterial foraging algorithm [16], and ant colony [17] methodshave been introduced.GAis widely used and is simpler and moreapplicable.In this paper, the bee algorithm (BA) is applied to minimizelow-order harmonics, as well as to satisfy the desiredfundamental component. Results including the probability ofreaching to a global solution and the effect of running times arecompared with those obtained by GA. Results confirm the effectivenessof the proposed algorithm and its superiority over GA.Experimental results are presented to confirm the simulationresults.

II. MULTILEVEL INVERTERS

A. Multilevel Inverter Topology

Acascaded multilevel inverter (see Fig. 1) has advantages thathave been presented in [18]. Few components, the absence ofextra clamping diodes or voltage balancing capacitors, and easyadjustment of the number of output voltage levels are some ofthem. Switching devices turn ON and OFF only once per cycleto overcome the switching loss problem.The cascaded multilevel inverter consists of a series of Hbridge(single-phase full-bridge) inverter units. Each full-bridgecan generate three different voltage outputs: +*V*dc, 0, and −*V*dc.However, all three multilevel inverters can produce staircasewaveform as shown in Fig. 2. The number of output phasevoltage levels in a cascaded multilevel inverter is 2*S* + 1, where*S* is the number of dc sources. For example, phase voltagewaveform for a 7-level cascaded multilevel inverter with threeisolated dc sources (*S* = 3) is shown in Fig. 2. Each H-bridgeunit generates a quasi-square waveform by phase-shifting theswitching 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$\theta 1$,$\theta 2$, and $\theta 3$, where *V*dc1, *V*dc2, and *V*dc3 are assumedto be equal. Considering equal amplitude of all dc sources, theFourier series expansion of the output voltage waveform, shownin Fig. 1, will be written as$V(\omega t)$ =∞where *Vn*is the amplitude of the *n*th harmonic. Switching anglesare limited between zero and $\pi/2$ ($0 \le \theta i < \pi/2$). Becauseof odd quarter-wave symmetric characteristic, harmonics witheven order become zero. Consequently, *Vn*becomes

$$V_n = \begin{cases} \frac{4V_{dc}}{n\pi} \sum_{i=1}^{S} \cos(n\theta_i) & \text{for odd ns} \\ 0 & \text{for even ns.} \end{cases} \quad (2)$$

The objective of SHEPWM is to eliminate the lower order harmonicswhile remaining harmonics are removed with filter. Inthis paper, without loss of generality, a 7-level inverter is chosenas a case study to eliminate its low-order harmonics (fifth andseventh). 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 seventhharmonics, three nonlinear equations with three angles areprovided

$$V_1 = \frac{4V_{dc}}{\pi}[\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3)]$$
$$V_5 = \frac{4V_{dc}}{5\pi}[\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3)]$$
$$V_7 = \frac{4V_{dc}}{7\pi}[\cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3)]. \quad (3)$$

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$$V_5 = \frac{4V_{dc}}{5\pi}[\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3)]$$
$$V_7 = \frac{4V_{dc}}{7\pi}[\cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3)]. \quad (3)$$

$$M \triangleq \frac{V_1}{12V_{dc}/\pi} \qquad (0 \le M \le 1). \quad (4)$$

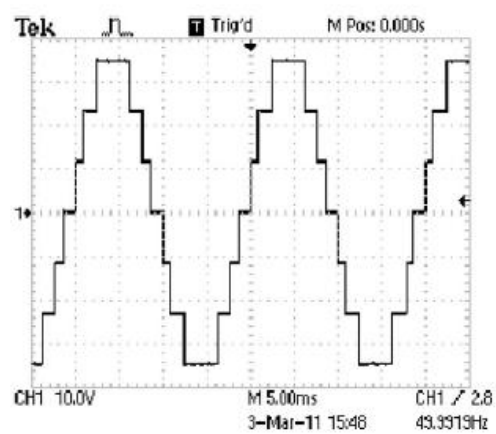
Here, M is between 0 and 1 to cover different values of V_1.

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 equation

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

Now, three switching angles, namely θ_1, θ_2, and θ_3, must be found with respect to the range of M.

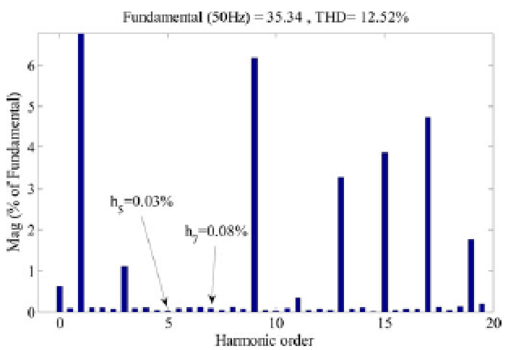
III. SA ALGORITHM



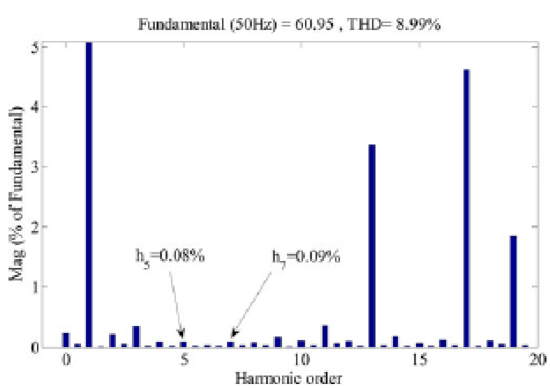
$x = 10{-}7$ is selected to be more reliable. for all run numbers, the CDF of BA is more than the CDF of GA. So, SA has better performance for finding solutions.

IV. EXPERIMENTAL RESULT

For verifying BA solutions, a 3-phase 2-kW hardware prototype7-level inverter as shown in Figure. It consists ofthree full-bridge inverters that are connected in a series form.DC source voltage of each H-bridge inverter is constant and isselected to be 12V. Also, the frequency of the output is assumed to be 50 Hz.



Switching angles are obtained offline by SA for the rangeof *M*. The angles are loaded in an 89s52 microcontrolleras a lookup table. For each *M*, 89s52 findsswitching 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 transferred to IGBT driver 7667 that is connectedto IGBT and supplies*Qge*that is required for turning IGBT ON.Figure shows the output phase voltage for*M* = 0.8. Switchingangles are shown in Table III. According to this pointis feasible. The data in Fig. 13 are extracted from the TektronixTDS1002B oscilloscope and related frequency spectrum is plottedwith FFT analysis of the Simulink/Powergui block. Fig. 14which shows the frequency spectrum confirms the results.Fig. 15 shows the output line voltage. Fig. 16 shows thefrequency spectrum of this waveform. Low-order harmonics aswell as triplen harmonics are removed.



V.CONCLUSION

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

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