ARTICLE IN PRESS

Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Selective harmonic elimination in inverters using bio-inspired intelligent algorithms for renewable energy conversion applications: A review

Mudasir Ahmed Memon[a,*], Saad Mekhilef[a,*], Marizan Mubin[a,*], Muhammad Aamir[b]

[a] Power Electronics and Renewable Energy Research Laboratory (PEARL), Department of Electrical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia
[b] Department of Electrical Engineering, Bahria University, Islamabad 44000, Pakistan

ARTICLE INFO

Keywords:
Renewable energy
Bio-inspired intelligent algorithms
Inverters
Selective harmonic elimination pulse width modulation
Energy conversion

ABSTRACT

Observing present scarcity of fossil fuel and emissions of greenhouse gases, electricity generated from Renewable Energy (RE) sources turns out to be the best alternative for generating the power. In RE system, the inverter is normally used to condition the DC power into AC to meet the requirements of load and transmission system. The inverter offers myriad benefits; however, the presence of harmonics (particularly low-order) in the output voltage affects the efficiency and performance of inverter, causes switching losses and decreases the lifetime of the system. In last three decades, significant research has been done to develop the efficient control technique for eliminating the unwanted harmonics. The preliminary review of existing control techniques revealed that the selective harmonic elimination pulse-width modulation (SHEPWM) is more proficient to eliminate the low-order harmonics. However, non-linear transcendental equations used in this technique pose a challenge to solve particularly for calculus-based methods. With the advent of powerful and low-cost computers, bio-inspired intelligent algorithms (BIAs) seem to be a better approach for solving these complex equations. This review paper presents the detailed principle operation of nine well-known BIAs and discusses their application in inverters for harmonic elimination (HE). Moreover, different objective functions are also discussed in this paper which is used by the researchers for HE. Additionally, the performance of five renowned BIAs, namely, Imperialist Competitive Algorithm, Particle Swarm Optimization, Differential Evolution, Bee Algorithm and Genetic Algorithm is critically evaluated. Their performance is analyzed in terms of accuracy, computational complexity, convergence speed, and a number of control parameters. The conclusion has been made on the basis of information extracted from the literature and evaluation results with future recommendations. This single paper covers all the essential information regarding HE in inverters, which will help researchers to design the efficient RE conversion system.

1. Introduction

Fossil fuel-based energy generation industries emit harmful greenhouse gases, such as CO_2 and methane; these gases cause climate change and adds in global warming [1–3]. Anthropogenic climate change can be reduced by generating the electricity using RE sources, such as biomass, the wind, and solar [1]. RE systems are beneficial because they consume nearly zero fossil fuel (e.g., coal, natural gas, and oil), require low maintenance, emit a small percentage of greenhouse gases, and are less costly than conventional energy generation systems in cases where transportation charges of fossil fuels are high [4].

The RE sources like tidal, biomass and solar generate electricity in DC form whereas the load and electrical transmission system utilize AC power. Thus, a converter is needed to convert DC energy into AC form [5,6]. In this situation, inverter converts DC voltages into AC [7–34]. Inverters are used in grid-connected [9,12] or stand-alone [35] RE systems to run a load or any equipment that requires AC power. Inverters are reliable, cost-effective, simple, and efficient devices for energy conversion [36–38]. The inverters are also used in energy transmission, compressors, high-voltage direct current lines, grinding mills and flexible AC transmission systems [39–45]. Due to prevalent applications of inverters in RE system and power electronics based industries, scholars in academia and industries are endlessly concentrating on the research and development of inverters.

In RE systems, Grid-connected solar farms augment the importance of inverters, which employ large-scale photovoltaic (PV) cells [46]. Wind turbines use inverters for the conversion of power [47]. Hybrid RE systems and backup systems also use inverters; in this

* Corresponding authors.
E-mail addresses: memon.mudasir@usindh.edu.pk (M.A. Memon), saad@um.edu.my (S. Mekhilef), marizan@um.edu.my (M. Mubin).

http://dx.doi.org/10.1016/j.rser.2017.08.068
Received 2 February 2017; Received in revised form 2 August 2017; Accepted 18 August 2017
1364-0321/

context, the most popular example is the wind–solar–battery installations in islands and remote areas [35,48,49]. AC appliances, such as motors, lighting systems, and electronic gadgets, are also driven through inverters [35,50,51]. In addition, inverters are used in energy-saving applications in cooling and heating systems. The integration of inverters with variable-speed drive helps in reduction of energy consumption of cooling compressors [50]. Moreover, inverters play an important role in the dynamic stability control and voltage regulation of electrical power systems [48,52]. Due to the widespread usage in RE and power industries, inverter becomes the indispensable part of current and future applications.

Inverters offer numerous advantages; however, their output voltage contains a significant amount of unwanted harmonics, which have negative effects on mechanical and electrical components of the system [53–56]. Among the harmonics, low-order harmonics are more dangerous to systems because they are closer to the fundamental frequency and have significant amplitude. The presence of harmonics in inverters increases switching losses in power switches which degrade the efficiency of RE system and deteriorates overall system performance. For example, it causes speed ripple and torque problem in the induction motor, and it reduces the reliability and lifetime of the system due to the torque pulsation, vibration, and mechanical fatigue. The presence of low-order harmonics in the inverter output voltage also creates undesirable and complicated problems at distribution system when injecting power into the electrical grid [57,58]. For instance, it affects the output power quality of electrical grid; and possibly causes unwanted islanding, voltage fluctuations, and malfunctioning in the protection devices which are connected at the grid side [59]. To overcome these problems, researchers have developed various modulation-based control techniques for eliminating the harmonics which improve performance and efficiency of the inverter [60]. Out of those developed techniques, selective harmonic eliminating pulse-width modulation (SHEPWM) exhibits greater performance because of its superior control over eliminating unwanted low-order harmonics from inverter output voltage [61].

In SHEPWM technique, complex transcendental equations are used to derive optimized firing angles which will force the unwanted harmonics to eliminate from inverter output voltage [62]. However, convergence to an optimum solution is sometimes difficult to achieve due to the involvement of sine and cosine functions which contain different frequencies. Furthermore, this problem becomes more severe in the case of an increase in a number of firing angles and level of the inverter. Despite these complexities, various numerical and algebraic methods like Newton-Raphson (NR) and resultant elimination theory, respectively are proposed to obtain the solution sets for HE. However, the main downside of the earlier technique is, they are based on good initial guesses, thus wrongly chosen guesses result in large iterative cycles and may diverge in extreme cases. The latter technique is computationally very much complex to calculate solutions in real time and their complexity further increases while working on high-level inverters [36–38].

Recently, most of the engineering problems are solved using optimization approach particularly using bio-inspired intelligent algorithms (BIAs) [63–67]. The main strength of these algorithms is, they are not fully dependent on the initial guesses and are also not computationally complex. Furthermore, BIAs are easy to understand and implement using low-cost powerful computers. In RE system, BIAs are applied in many applications [68–84] but their major utilization is HE from the output of the inverters [85–87]. BIAs include the algorithms like Bee Algorithm (BA), Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Differential Evolution (DE) [64]. The BIAs utilize an objective function that contains non-linear transcendental equations of low-order harmonics and fundamental. This technique minimizes the objective function to get the optimized firing angles which eliminate unwanted harmonics. The performances of BIAs significantly depend upon the formulation of an objective function. The researchers mostly use different objective function in their research to effectively eliminate the unwanted harmonics.

Over the years different BIAs and objective functions have been proposed and published in the literature to solve HE problem of the inverter. However, there is the absence of review article which presents a comprehensive study on this subject. Hence, it is necessary to sum up the efforts exerted to address the HE problem using BIAs and also gather the different objective functions used by the researchers in a single article. The objective of this paper is to explain nine well-known BIAs in detail with full principal operation and their applications in solving HE problem. Additionally, different objective functions used by the researchers for HE are also presented in this paper. Furthermore, the performance of five prominent BIAs is also critically evaluated in terms of accuracy, computational complexity, convergence speed, and a number of control parameters. The selected BIAs are programmed in MATLAB and firing angles are calculated for a 7-level inverter. Based on the information presented in the literature and comparison results, some directions for future research are also given to get more advantages from SHEPWM technique. This single article will be useful for researchers and engineers who are working to improve the efficiency and performance of inverters, particularly in RE systems.

2. Overview of inverters and SHEPWM technique

2.1. Topologies of inverters

Inverters are classified into two categories: 1) current source inverter (CSI) and 2) voltage source inverter (VSI) [45]. RE systems mostly use VSI [12]; therefore, this study is focused on VSI. The VSI is divided into two categories: 1) two-level inverter (generally called as VSI) and 2) multilevel VSI (MVSI) [60]. VSI can generate unipolar or bipolar output voltage waveforms, whereas MVSI generates staircase output voltage waveforms. The latter category provides the output similar to a sinusoidal wave by summing up different DC voltages attached to the input of an inverter. A transformerless structure, low switching losses, high-power quality signals, low electromagnetic interference (EMI), and reduced harmonic distortion are the main advantages of MVSIs [36–38]. The topologies of MVSIs are divided into two types. The first type uses separate DC sources, whereas the second type uses a common DC source for multilevel operation. The cascaded H-bridge (CHB) topology uses separate DC sources, whereas the flying capacitor (FC) topology and the neutral-point-clamped (NPC) or diode-clamped topology use a common DC source for staircase output waveform [39–45]. The structures of these basic topologies are shown in Fig. 1. Various hybrid topologies have also been developed from basic structures, which use less number of components [88–95]. In RE systems, CHB is the most commonly used topology as it has a modular, repetitive, and simple structure. Moreover, this topology also uses less number of components as indicated in Table 1 [7,9,12–34]. This topology is also preferred due to its feature of using separate DC sources for multilevel operations. RE sources, particularly PV cells can be directly connected to the separate cells of CHB, and inverter provides the voltage (sum of all the cells) in staircase output form [12].

2.2. SHEPWM technique

The output voltage quality of an inverter is measured by the total harmonic distortion (THD) factor [51], which is given in Eq. (1):

$$THD = \frac{\sqrt{\sum_{i=2}^{n} V_i^2}}{V_1} \tag{1}$$

where V_i is the voltage of particular harmonics, and V_1 is the fundamental voltage. The efficiency of energy conversion (DC/AC) is also depends on the THD factor [96]. Various organizations have set and