Energy Conversion and Management 91 (2015) 83–92

Contents lists available at ScienceDirect

Energy Conversion and Management

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

# Power control based on particle swarm optimization of grid-connected inverter for hybrid renewable energy system

Pablo García-Triviño [a], Antonio José Gil-Mena [a], Francisco Llorens-Iborra [a], Carlos Andrés García-Vázquez [a], Luis M. Fernández-Ramírez [a,*], Francisco Jurado [b]

[a] Research Group in Electrical Technologies for Sustainable and Renewable Energy (PAIDI-TEP-023), Department of Electrical Engineering, University of Cádiz, 11202 EPS Algeciras, Algeciras (Cádiz), Spain

[b] Research Group in Research and Electrical Technology (PAIDI-TEP-152), Department of Electrical Engineering, University of Jaén, 23700 EPS Linares, Linares (Jaén), Spain

ARTICLE INFO

*Article history:*
Received 23 September 2014
Accepted 25 November 2014
Available online 17 December 2014

*Keywords:*
Grid-connected inverter
Hybrid renewable energy system
Optimization
Power control

ABSTRACT

This paper is focused on the study of particle swarm optimization (PSO)-based PI controllers for the power control of a grid-connected inverter supplied from a hybrid renewable energy system. It is composed of two renewable energy sources (wind turbine and photovoltaic – PV – solar panels) and two energy storage systems (battery and hydrogen system, integrated by fuel cell and electrolyzer). Three PSO-based PI controllers are implemented: (1) conventional PI controller with offline tuning by PSO algorithm based on the integral time absolute error (ITAE) index; (2) PI controllers with online self-tuning by PSO algorithm based on the error; and (3) PI controllers with online self-tuning by PSO algorithm based on the ITAE index. To evaluate and compare the three controllers, the hybrid renewable energy system and the grid-connected inverter are simulated under changes in the active and reactive power values, as well as under a grid voltage sag. The results show that the online PSO-based PI controllers that optimize the ITAE index achieves the best response.



## 1. Introduction

Hybrid renewable energy systems (HRESs) use two or more renewable energy sources to increase the renewable generation capacity, and one or more energy storage devices to have energy support/storage [1]. In these HRESs, the primary energy sources are commonly wind turbine/s and PV solar panels (renewable energy sources), which operate whenever there is wind speed and/or solar irradiance. The energy storage devices commonly used are batteries, and hydrogen systems (fuel cell, electrolyzer and hydrogen tank), which has received considerable attention in recent years [2]. In the hydrogen system, the electrolyzer produces the hydrogen, which is stored in a tank to supply the fuel cell. The excess of renewable energy can be stored in the battery or as hydrogen produced by the electrolyzer, whereas the deficit of renewable energy can be provided by the battery and/or fuel cell [3]. This configuration improves the grid integration capacity, the degree of controllability and operability of the HRESs. In fact, the capacity of adapting unregulated power generated from renewable sources to a specific power demanded by the grid is increased, since the energy storage devices can be used to provide/store power when possible. These features were analyzed and discussed in the survey on grid-scale energy storage applications in renewable energy integration presented in [4].

HRESs present a common DC bus to which all the energy sources are connected. The most used topologies are the parallel hybrid and series hybrid. In the parallel hybrid topology, all the energy sources are connected to the common DC bus through DC–DC power converters, whereas, in the series hybrid topology, some energy source (commonly some energy storage device) is directly connected to the common DC bus without DC–DC power converter. An energy efficiency analysis of the commonly used series and parallel hybrid topologies in hybrid power systems was presented in [5]. The energy efficiency for the multiport power converter used in series and parallel hybrid power sources was studied in [6]. In this work, a hybrid configuration with all the energy sources connected to the common DC bus through DC–DC power converters has been adopted, as it is usual in HRESs [7].

The management of the energy sources is achieved by the energy supervisory system. It is responsible for controlling the energy sources of the HRES and their power converters in order

* Corresponding author. Tel.: +34 956 028166; fax: +34 956 028001.
*E-mail addresses:* pablo.garcia@uca.es (P. García-Triviño), antonio.gil@uca.es (A.J. Gil-Mena), francisco.llorens@uca.es (F. Llorens-Iborra), carlosandres.garcia@uca.es (C.A. García-Vázquez), luis.fernandez@uca.es (L.M. Fernández-Ramírez), fjurado@ujaen.es (F. Jurado).

http://dx.doi.org/10.1016/j.enconman.2014.11.051
0196-8904/

to generate the power demanded by the grid, using optimally both renewable energy sources and energy storage devices. Therefore, the strategy adopted in the energy supervisory system is essential for the right operation of the HRES. In the literature, there are many papers related to energy management strategies. These strategies are mainly designed to track the demanded power, to use optimally the energy sources and to regulate the DC bus voltage of the HRES. Normally, the energy supervisory systems are based on flowchart or states control, because they are easy to implement and really effective. In [8], a HRES composed of PV panel, fuel cell, battery and supercapacitor was controlled by a flowchart strategy with a simple on/off shunting of energy sources and sixteen operating scenarios. A energy management system based on states control, taking into account the generation cost for each source and premises such as maintaining the energy stored in the energy storage devices between certain operation limits, was adopted in [9] for a HRES with wind turbine, PV panels, hydrogen system and battery. A simple alternative to operate a HRES based on wind turbine, PV panel, fuel cell, battery and supercapacitor based on load-following control and energy harvesting concepts was used in [10]. Other more complex energy supervisory systems, such as fuzzy logic control, artificial neural network, adaptive neuro fuzzy inference system and predictive control, have been also applied to energy supervisory systems of HRESs. Ref. [11] presented an energy supervisory system based on fuzzy logic for a HRES composed of wind turbine, PV panel, hydrogen system and battery. An optimized fuzzy logic controller for a wind turbine/PV/hydrogen/battery HRES based on the particle swarm optimization algorithm was developed in [12]. An artificial neural network controller for the energy management of a HRES integrated by wind turbine, PV panels, hydrogen system and battery was proposed in [13]. Ref. [14] evaluated an energy supervisory system based on adaptive neuro-fuzzy inference system for a wind turbine/PV/hydrogen/battery HRES. Energy dispatch strategy based on predictive control for a PV/wind/diesel/battery HRES was presented in [15]. Ref. [16] detailed an energy supervisory system based on model predictive control for a PV/wind turbine/hydrogen/battery HRES. In this work, a simple strategy based on states control has been implemented for the management of the energy sources of the HRES under study, because the goal is focused on the inverter control.

The DC/DC converters connected to each energy source allow controlling the energy flow between the sources adapting their variable voltages to the constant DC bus voltage of the HRES. The DC/DC converters of the renewable energy sources are controlled by Maximum Power Point Tracking (MPPT) strategy to extract the maximum power from the renewable source. The converters of the energy storage devices are controlled in order to allow the charge or discharge of the device, when possible and required. In hybrid systems based on fuel cells, the use of nonlinear control can improve the performance and durability of the fuel cell [17] and the response of the inverter [18].

The energy available in the common DC bus of the HRES is exchanged with the grid through a three-phase voltage source inverter (VSI). The inverter control is essential to achieve the desired exchange of active and reactive power to the grid. In the control scheme, the three-phase grid current and voltage waveforms are transformed by a reference frame rotating synchronously with the grid voltage in direct-quadrature ($d$–$q$) values in order to achieve the decoupled control of the active and reactive power. The control scheme usually presents two cascade control loops [19]: (1) an external loop (power/voltage loop) for controlling the DC bus voltage or the active power and the reactive power delivered to the grid; (2), and an internal loop (current loop) for controlling the grid current.

The most widely used option in the power/voltage control loop is based on proportional–integral (PI) controllers due to their simplicity and easy implementation [19]. Ref. [20] presented the control of a grid-connected hybrid system composed of wind turbine, PV panels, supercapacitors and battery, and Ref. [21] detailed the control of a grid-connected PV-battery hybrid system, in which the power/voltage control loop of the inverter was performed by PI controllers. These external controllers determine the *dq* components of the current reference for the current loop. Fuzzy logic and adaptive neuro-fuzzy inference system (ANFIS) controllers have been also used in the power/voltage control loop. A voltage control loop based on fuzzy logic was applied to a grid-connected three-level three-phase inverter for distributed generation in [22]. Ref. [23] compared the real-time implementation of PI and fuzzy logic controllers in the power control loop of a grid-connected voltage source inverter. An ANFIS-based power control was applied to the three-phase inverter of a grid-connected HRES in [14]. Ref. [24] evaluated the real-time implementation of an ANFIS controller for the power control of a renewable interfacing inverter in three-phase four-wire distribution network. In the case of the current control loop, different control schemes have been applied, such as PI controllers, hysteresis controllers, proportional–resonant controllers, predictive controllers, and $H_\infty$ robust controllers. Ref. [25] presented a survey on the current control techniques for three-phase voltage source inverters. A three-phase grid connected inverter for PV system was described in [26], in which the inverter current control was performed by PI controller. The renewable interfacing inverter detailed in [24] was controlled by hysteresis current controller. Proportional–resonant controller was applied to the current control loop of the grid connected inverter used in [22]. Ref. [27] illustrated a predictive current control method and its application to a voltage source inverter. In [28], a robust current control scheme based on $H_\infty$ controller for grid-connected inverters was evaluated and compared with the conventional PI controller.

Grid-connected inverters supplied from HRESs have to operate under fluctuating conditions, both because of nature fluctuating of the energy generated by the HRES and because of changes in the grid variables (grid voltage or frequency). As a result, the input and output conditions of the inverter, such as the energy available in the DC bus and the DC bus voltage (inputs) and the grid voltage (output), can vary, leading to changes in the inverter operating point. This hinders the optimal design of the inverter control, particularly in the case of conventional PI controllers, and may result in non-optimal operation of the inverter [24].

This paper describes and evaluates optimal PI controllers for the active and reactive power control of a three-phase grid-connected inverter supplied from the HRES (wind turbine and PV solar panels) with energy support (batteries and hydrogen system – fuel cell and electrolyzer). In fact, the main contribution of this paper is the on-line self-tuning based on PSO of the PI controllers for the power control loops of the HRES inverter. Two PSO algorithms are implemented for the on-line self-tuning of PI controllers: the first one tries to minimize the error, and the second one the ITAE index. Conventional PI controllers, in which the gains are tuned offline by using a PSO algorithm, are used to compare the performance of the online PSO-based PI controllers. The grid-connected inverter under study is simulated under different operating conditions (changes in the active and reactive power and grid voltage sag), and the responses obtained with each controller (conventional PI