Energy Conversion and Management 65 (2013) 41–49

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

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

Particle swarm optimization based fuzzy logic controller for autonomous green power energy system with hydrogen storage

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ARTICLE INFO

Article history:
Received 12 June 2012
Received in revised form 13 August 2012
Accepted 21 August 2012
Available online 11 October 2012

Keywords:
Fuzzy logic controller
Hybrid green power system
Optimization
Operation and maintenance costs
Loss of power supply probability

ABSTRACT

The objective of this study is to develop an optimized fuzzy logic controller (FLC) for operating an autonomous hybrid green power system (HGPS) based on the particle swarm optimization (PSO) algorithm. An electrolyzer produces hydrogen from surplus energy generated by the wind turbine and photovoltaic array of HGPS for later use by a fuel cell. The PSO algorithm is used to optimize membership functions of the FLC. The FLC inputs are (a) net power flow and (b) batteries state of charge (SOC) and FLC output determines the time for hydrogen production or consumption. Actual data for weekly residential load, wind speed, ambient temperature, and solar irradiation are used for performance simulation and analysis of the HGPS examined. The weekly operation and maintenance (O&M) costs and the loss of power supply probability (LPSP) are considered in the optimization procedure. It is determined that FLC optimization results in (a) reduced fluctuations in batteries SOC which translates into longer life for batteries and the average SOC is increased by 6.18% and (b) less working hours for fuel cell, when the load is met by wind and PV. It is found that the optimized FLC results in lower O&M costs and LPSP by 57% and 33%, respectively, as compared to its un-optimized counterpart. In addition, a reduction of 18% in investment cost is achievable by optimal sizing and reducing the capacity of HGPS equipment.

1. Introduction

Solar and wind energy are inexpensive, environmental friendly, non-depletable, and could serve as potential sources of alternative energy [1–3]. A green power system (GPS) that benefits from solar and wind energy often encounters noticeable limitations that originate from the intermittent nature of its contributing source [4]. To overcome the intermittency problem in power generation and increase reliability to meet continuous loads, two or more systems are used I hybrid from in conjunction with storage devices [5]. While batteries have been used to reduce or compensate for the intermittency caused by adverse effects of time varying weather conditions, they have low useful life and hydrogen-based fuel cells are also integrated into hybrid GPS (HGPS) as viable solutions [6,7].

To regulate the energy flow among the different components of a HGPS, a control system is necessary. Numerous studies have been performed on control of HGPS with hydrogen storage. In a study, a neural network control system is programmed to learn over time to use system resources more efficiently by adjusting the energy storage strategy to variations in power production and demand [8], but it needs historical data to be efficient. In another study, an un-optimized fuzzy logic controller (FLC) is examined to determine the appropriate hydrogen rate of production/consumption for a HGPS [9], however, the simulation results showed that the system does not provide enough input energy to power a typical residential load for a very long time. For a HGPS, comprised of photovoltaic (PV) array, wind turbine, and fuel cells, FLC is employed to achieve maximum power tracking for delivery to a DC bus [10,11].

As the difference in cost of electricity generated by HGPS and non-renewable sources is continuously decreasing due to technological advancements in manufacturing of equipment, it is anticipated that optimal control of HGPS would make the overall system performance even more economical [12]. The optimization of FLC using evolutionary programming has been utilized for different systems, for example, the genetic algorithm (GA) is applied for the simultaneous design of membership functions and rule sets for a FLC of the steam generator water level [13]. This type of controller is smaller and its response is faster than that of a well-tuned proportional–integral–derivative (PID) controller and provides satisfactory performance, although it has a small number of rules. A GA-fuzzy-PID controller is examined for enhancement of energy efficiency of a dynamic energy system [14] and the results show that GA-fuzzy-PID controller, in comparison with PID controller, achieves higher energy efficiency by lowering energy costs. The GA is also used for simultaneously finding optimum design of FLC membership functions and control rules, where the controller

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0196-8904/$ - see front matter
http://dx.doi.org/10.1016/j.enconman.2012.08.012

is used as a maximum-power-point tracker for an autonomous PV panel [15] and the results show improvement in design optimization. The particle swarm optimization (PSO) algorithm is used in a study for tuning a FLC that controls a robot trajectory [16] and it is found to be more accurate with less or no deviation from the trajectory, as compared to a PSO–PID controller. Another application of PSO for designing an optimal FLC for load frequency control of isolated wind-natural gas hybrid power system is reported in [17] and simulation results show that the performance of proposed controller is superior to a PID controller in terms of settling time, overshoot, and robustness under load change. In another study, the PSO algorithm is used for optimizing membership functions of a FLC that controls an autonomous PV panel [18], where the optimized FLC is able to provide maximum energy to the system loads while maintaining a higher average state of charge (SOC) of battery.

As summarized in Table 1, the review of literature shows that studies on optimized FLC for power flow regulation and energy management of HGPS are lacking. The objective of this study is to develop an optimized FLC for operating an autonomous HGPS based on the PSO algorithm. The PSO algorithm is used to optimize the FLC membership functions. Actual data for weekly residential load, wind speed, ambient temperature, and solar irradiation are used for performance simulation and analysis the HGPS. The weekly operation and maintenance (O&M) costs of HGPS is accounted for and, for evaluating reliability of HGPS power production under varying weather conditions, the loss of power supply probability (LPSP) is considered [19].

The remaining parts of this study are organized as follows. In Section 2, the HGPS model is introduced. The analysis section describing the FLC structure, membership functions, and rules as well as the PSO algorithm used for optimizing the FLC membership functions is presented in Section 3. Sections 4 and 5 provide the simulation results and conclusions and recommendations, respectively.

2. HGPS model

As shown in Fig. 1, the HGPS utilizes a wind turbine, a PV array, an electrolyzer, a fuel cell with hydrogen storage tank, and a stack of batteries to meet the load via a DC bus and an inverter [9], where the power flow is regulated by an optimized FLC.

A wind turbine and a PV array are used as indigenous green power production resources. An electrolyzer is used for production and storage of the excess energy in form of hydrogen and a proton exchange membrane fuel cell is used for re-utilization of stored hydrogen to generate electricity. A battery stack is also used to store short-term energy [20]. The buck and boost converters control the electrolyzer and fuel cell power, respectively.

For HGPS simulation in this study, the actual hourly data for load power, wind speed, ambient temperature, and solar irradiation available for the last week of March 2008 in north of Iran are shown in Fig. 2.

2.1. Wind turbine

Based on local wind speed and equipment characteristics, the amount of power produced by wind turbine (kW) is given by [21]

$$P_{wind}(t) = \begin{cases} P_{max,wind} \cdot \frac{V(t)-V_C}{V_R-V_C} & if\ V_C \leqslant V(t) \leqslant V_R \\ P_{max,wind} & if\ V_R \leqslant V(t) \leqslant V_F \\ 0 & if\ V(t) < V_C \cup V(t) > V_F \end{cases} \quad (1)$$

where $V(t)$ is wind speed at time t(m/s), $P_{max,wind}$ is nameplate power rating of wind turbine (kW), V_F, V_R and V_C are the characteristic parameters determined by the wind turbine power curve provided by the manufacturer (m/s), as shown in Fig. 3. The wind turbine starts producing power at a wind speed of 3.5 m/s and reaches rated power at wind speed of 9.5 m/s. At wind speeds higher than 25 m/s, the controller puts the wind turbine on the brake [22].

Table 1
Summary of HGPS studies in the literature.

Reference	Wind	PV	Battery	Hydrogen	Controller	FLC	Optimization
[1]	•	•	•				•
[2]	•	•			•		
[3]	•	•					•
[4]	•	•					•
[5]	•	•	•	•	•		
[6]	•	•		•	•		
[7]	•	•		•	•		
[8]		•	•	•	•		
[9]	•	•	•	•	•		
[10]	•	•		•	•	•	
[11]	•	•		•	•	•	
[12]		•	•		•		
[13]					•	•	•
[14]					•		•
[15]		•			•	•	•
[16]					•	•	•
[17]	•				•	•	•
[18]		•	•		•	•	•
[19]	•	•	•		•		
[20]	•	•	•	•	•		•
[21]	•	•					•
[23]	•	•	•		•		•
[27]					•	•	
[28]	•	•					•
[29]		•	•	•	•		
[30]		•			•		
[31]	•		•	•			•
[32]	•	•	•	•			•
This study	•	•	•	•	•	•	•