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Reliability/cost-based multi-objective Pareto optimal design of stand-alone wind/PV/FC generation microgrid system

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ABSTRACT

The main goal for designing hybrid wind–solar generating microgrid systems is reliable supply of load, under varying weather conditions, with the minimum cost and maximum reliability. In this paper, a hybrid wind-solar generation microgrid system with hydrogen energy storage is designed for a 20-year period of operation using novel multi-objective optimization algorithm to minimize the three objective functions namely annualized cost of the system, loss of load expected and loss of energy expected. System costs involve investment, replacement and operation and maintenance costs and the major components of system may be subjected to failure. The simulation results based on multi-objective particle swarm optimization for different cases reveal the impact of components outage on reliability and cost of the system. In addition, an approximate method for reliability evaluation of hybrid system is presented which lead to reduce computation time. Simulation results show effectiveness of proposed multi-objective algorithm to solve optimal sizing problem in contrast with traditional single objective methods.

1. Introduction

Renewable energy resources have enormous potential to enhance diversity in energy supply markets, secure long-term sustainable energy supply, and reduce local and global atmospheric emissions [1,2]. Due to the small capacity of renewable energy sources, the use of Distributed Energy Resources (DER) is of great interest that can provide the power of demand side alone or in a small electricity grid. Microgrid is a small-scale power grid in the low voltage that must be able to locally solve energy issues and enhance the flexibility and can operates either in grid-connected or islanding (autonomous) mode [3–6]. Photovoltaic (PV) and Wind Generation (WG) units are widely used to supply load in remote and rural regions [7–9]. A drawback common to these units, is unpredictable nature of solar and wind energy sources. Moreover, the variations of these sources may not match with the time distribution of demand. These drawbacks result in serious reliability concerns in both design and operation of PV and WG systems. Over sizing is an approach to overcome reliability problem, however, it may be costly. As another approach, hybrid PV/WG systems efficiently combine complementary characteristics of solar and wind sources to enhance the system's reliability and reduce its costs [10–12].

Block diagram of such a system is demonstrated in Fig. 1. Generating units are connected to a common Direct Current (DC) bus and a combination of a Fuel Cell (FC) stack, an electrolyzer, and a hydrogen storage tank is used as the Energy Storage System (ESS). Hydrogen as a suitable storage medium in renewable energy systems that is the subject of various studies in recent years [13–15]. This system performs both long-term and short-term storage duties and, sometimes, a super capacitor may enhance system's dynamic response for very short-term purposes [8]. The power is converted to Alternating Current (AC) via a DC/AC converter to supply an AC load.

However, a diesel generator can performs storage task with a lower investment cost. Major disadvantages of diesel-based systems are their need for fuel and their emissions. In contrast, hydrogen-based storages are emission free and they do not need any supply of fuel. Moreover, according to expectation of increase in fuel price and extreme reductions in FC costs, using hydrogen-based systems will be economically reasonable in future [17–19]. Also, in hybrid PV/WG/diesel systems, it is not possible to store surplus solar and wind energy during the good seasons. In contrary,

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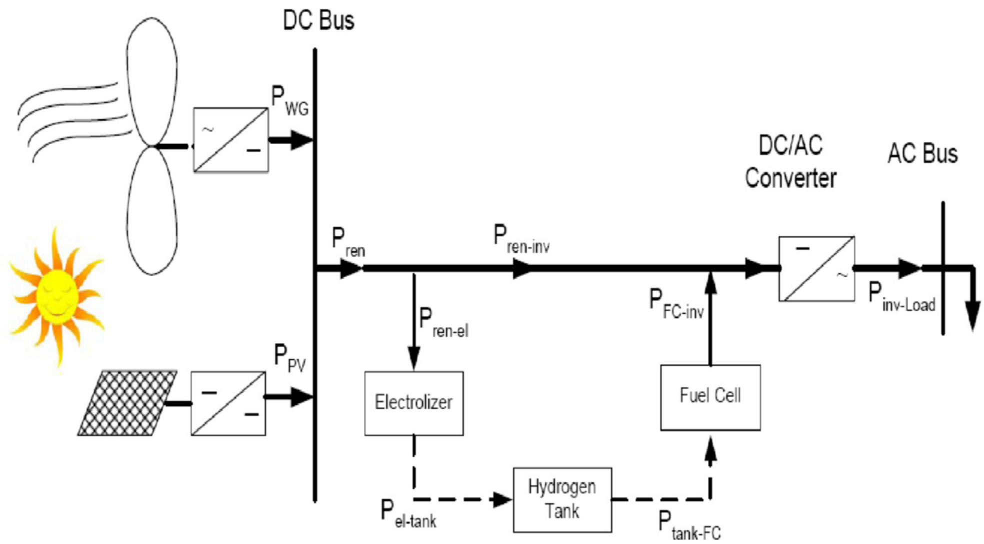

Fig. 1. Block diagram of a hybrid wind/Photovoltaic generation unit with hydrogen based ESS.

in proposed hydrogen-based storage system, electrolyzer converts the excess energy into chemical form, i.e. produces hydrogen, and stores in the hydrogen tank. When the wind speed or solar radiation decreases or a peak demand occurs, the hydrogen can be delivered to the load through the FC [20]. In addition, with accessibility of hydrogen sources, e.g. when a hydrogen network is available; the FC system can independently supply the load with a high reliability [21].

Because of intermittent characteristic of wind speed and radiation, most important challenge in design of such systems is reliable supply of demand under different weather situations considering operation and investment costs of components. Hence, the goal is optimal design of a hybrid system for reliable and economical supply of the load [15]. In this way, literature offers a variety of methods for optimal designing of hybrid PV/WG generating systems [7,9,10,15,20,22–28].

Nonlinear programming has been used in Ref. [25] to find the optimal size and location of grid-connected wind turbines based on simulation of various scenarios. Simple iterative search algorithms have been used for optimal sizing of hybrid wind/PV system with battery storage [20,29–35], Deficiency of power supply probability (DPSP) [29] and Loss of power supply probability (LPSP) [35,36] have been used as the technical criteria in iterative solution for optimal sizing of hybrid wind/PV systems with battery storage. In Ref. [26] Genetic Algorithm (GA) finds optimal sizes of the hybrid system components. In some other works, Particle Swarm Optimization (PSO) has been successfully implemented for optimal sizing of hybrid stand-alone power systems, assuming continuous and reliable supply of the load [22,28,37–39]. GA and Preference-Inspired Co-Evolutionary Algorithm (PICEA) have been used in Refs. [7,27] to find optimal size of a wind/PV/battery power system subject to reliability index of Loss of Power Supply Probability (LPSP). However, they do not consider the outage probabilities of system components such as wind turbines and PV arrays. In Ref. [24], a methodology for calculation of economic costs of power interruptions for different user sectors and interruption durations has been developed.

Literature on optimal designing of hybrid energy systems, does not consider reliability issues in depth. For instance, some very given phenomena that may extremely affect system's reliability and cost, such as failures and outages of generating units are usually ignored. However, reliability assessment is relevant for any engineering system [40]. In renewable energy studies, for either stand-alone or grid-connected system, reliability of different combination of renewable systems with different configuration, component specifications, load profile, and available renewable sources, can be solely evaluated.

Mawardi et al. [41] studied the impacts of uncertainties in operating parameters and reliability of a Proton Exchange Membrane Fuel Cell (PEMFC) and concludes that, uncertainty and reliability must be considered in designing stage of any robust and applicable system. Finally, it suggests that a stochastic modeling framework should be interfaced with a numerical optimization scheme to provide a robust design tool for stochastic optimization under uncertainty.

This suggestion was a great motivation to consider the impact of component reliabilities, on economical design of stand-alone renewable systems. Therefore, in Ref. [10], as the first step toward designing of an economical, robust, and reliable hybrid wind/PV power system, the outage probabilities of PV arrays and WGs have been considered. But, further studies revealed that the availability of DC/AC converter has an extreme influence over the system's reliability as the only single cut-set in reliability diagram of the hybrid system, [40]. Later, Kashefi-Kaviani et al. [39] investigated the problem more carefully. The PSO has been used to minimized objective function include Annualized Costs (AC) of investment, replacement, and Operation and Maintenance (O&M), as well as costumers' dissatisfaction costs as a Single Objective Optimization (SOO) problem. In fact, the reliability indices have been used to be changed in the form of cost and added to the cost function. But, reliability indices have been not considered independently as an objective function.

Multi-Objective Optimization (MOO) methods have also been used to design and optimize hybrid energy systems [29,42]. In Ref. [19], a hybrid PV-wind-diesel-hydrogen-battery system has been designed using a triple multi-objective algorithm minimizing total net present cost, CO_2 emissions, and the unmet load as three objective functions by using Multi-Objective Evolutionary Algorithm (MOEA) and GA. Multi-objective linear Programming (MOLP) has been used to optimize economic and environmental objective functions in a distributed energy system including PV, fuel cell and gas engine for Combined Heat and Power (CHP) plants to provide electrical and thermal demands [43].

In this paper, Multi-Objective Particle Swarm Optimization