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Optimized operation combining costs, efficiency and lifetime of a hybrid renewable energy system with energy storage by battery and hydrogen in grid-connected applications

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

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

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

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ABSTRACT

This paper describes a novel energy management system for the optimized operation of the energy sources of a grid-connected hybrid renewable energy system (wind turbine and photovoltaic) with battery and hydrogen system (fuel cell and electrolyzer). A multi-objective optimization problem based on the weight aggregation approach is formulated by combining three objective functions (operating costs, efficiency and lifetime of the devices) that can conflict with each. The multi-objective function to be optimized by the energy management system is obtained by solving the problem for all the possible cases. Then, the weights that provide the minimum value of the multi-objective function are selected. As the results demonstrate, the multi-objective function becomes a single-objective function that differs according to the net power (power to be generated by/stored in the energy storage devices) and has to be solved in the energy management system of the hybrid system. It simplifies considerably the multi-objective problem implemented in the energy management system, while taking into account the three control objectives that can conflict with each other, which is the main contribution of this paper. This optimal energy management system is solved using the Particle Swarm Optimization (PSO) method, tested by simulations of the hybrid power generation system throughout 25 years (the expected lifetime of the system), and compared with the results obtained by the energy management systems based on optimizing each single-objective function separately, and by that based on optimizing the multi-objective function combining the three single-objective functions equally weighted. The results demonstrate that this energy management system achieves reasonable operating costs, efficiency and degradation of the devices.

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

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Introduction

Hybrid power generation systems integrate several energy sources, and use the energy resources efficiently to provide the power demanded by a load (stand-alone applications) or by the grid (grid-connected applications). Commonly, renewable energy sources (wind turbine/s and/or photovoltaic solar panels) are combined with energy storage devices (batteries, hydrogen-based system, etc.) to increase their generation capacity and to gain energy support/storage capability [1]. Hence, hybrid power generation systems can respond efficiently and effectively to changes in the available energy and/or demand [2,3].

An energy management system is essential for the proper operation of hybrid power generation systems. In fact, the optimal use of the energy sources can be achieved by implementing optimization-based control methods [4], in which an optimization problem is formulated and solved to decide how the energy sources must operate.

The optimization problem is formulated through an objective function, where the goal is to find the optimal solution for the optimization problem. The objective function mostly used is the cost minimization [5–7], although other objective functions, such as efficiency maximization [6], fuel consumption minimization [8], or energy sources lifetime maximization [6], have also been used. The authors studied in Ref. [6] three optimal energy management systems for a grid-connected hybrid system with renewable energy sources (wind turbine and PV) and energy storage systems (battery and hydrogen), each one optimizing a different objective function. The three objective functions implemented in the control system were the cost minimization, the efficiency maximization and the energy sources lifetime maximization. The results showed that each energy management system achieved the best results in its designed target (control objective). However, some of these objective functions can be inherently contradictory and conflict with each other. The use of multi-objective optimization techniques helps to find an optimal solution among different objectives. In these techniques, the goal is usually to find a representative set of Pareto optimal solutions, quantify the trade-offs between the multiple different objectives, and help the decision maker to choose an optimal solution that satisfies certain priorities and preferences [9]. While in the existing literature on hybrid power generation systems there are many research works on optimal design/sizing based on multi-objective optimization [10,11], the works on control methods using multi-objective optimization are scarce. An operational optimization based on costs and power quality was applied in Ref. [7] to a stand-alone hybrid renewable energy system integrated by a wind turbine, photovoltaic solar panels and a battery. An optimal energy management system for a stand-alone hybrid photovoltaic/fuel cell/battery power system was proposed in Ref. [8]. It combined two objectives, i.e.: to reduce the hydrogen consumption and to improve the battery performance. A stand-alone hybrid system composed of a wind turbine, photovoltaic solar panels, a diesel generator and a battery was controlled in Ref. [12] by an energy management system which optimized the overall operating and environmental costs.

This paper is a continuation of the work presented by the authors in Ref. [6], in which, as mentioned above, three energy management systems, each one based on optimizing a different single-objective function, were analyzed and compared for the optimal control of a grid-connected hybrid system integrating five energy devices: a wind power generator, photovoltaic solar panels, a battery, a fuel cell and an electrolyzer. The energy management systems were responsible for the operation of the hybrid system in order to produce the demanded power and the optimal energy dispatch among the energy storage devices (battery, fuel cell and electrolyzer). The objective of the first energy management system was to minimize the operation costs, the second one to maximize the efficiency, and the third one to optimize the lifetime of the energy storage devices. The main contribution of this paper is to present and evaluate a new energy management system based on multi-objective optimization for the same grid-connected hybrid power generation system considered in Ref. [6]. The multi-objective optimization problem implemented in the control system combines the three single-objective functions (control objectives) that were studied separately in Ref. [6], i.e. operating costs, efficiency and lifetime of the energy storage devices, which can conflict with each other. The optimization problem is solved by PSO due to its simplicity, convergence speed and robustness [13]. As a result, the battery, fuel cell and electrolyzer power are determined by the energy management system from the available power, the grid demand, the battery state-of-charge (SOC) and the hydrogen level. The main conclusion of this work is that the multi-objective optimization problem combining the three single-objective functions at the same time can be considerably simplified if the net power (power to be generated by/stored in the energy storage devices) is used as key control parameter. In fact, for each net power, the optimized multi-objective function (the minimum value of the multi-objective function) is achieved by optimizing only a single-objective problem function, since the optimal combination of weights (taking into account that the sum of weights must be equal to 1), that varies with the net power, is one in which only the weight of a single-objective function is equal to 1 and the rest of weights equal to 0. To evaluate this multi-objective optimization-based energy management system, the response of the hybrid power generation system is simulated and compared with those obtained by the energy management systems based on optimizing each single-objective function separately and by that based on optimizing the multi-objective function combining the three single-objective functions equally weighted.

This article is organized as follows. After the introduction, the multi-objective problem is formulated in Section Problem formulation, which includes the objective functions, the constraints and the PSO algorithm. Section Case