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Technical and economic effects of charge controller operation and coulombic efficiency on stand-alone hybrid power systems

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ABSTRACT

This paper presents a study evaluating the effects of charge controller operation and coulombic efficiency on stand-alone hybrid power systems. The model used in the study makes it possible to consider the uncertainty related to renewable resources, fuel cost, the battery bank's lifetime, energy demand, charge controller operation, and coulombic efficiency. As a case study, a hybrid system installed in Zaragoza, Spain, was analysed. The system includes photovoltaic panels, a wind turbine, a conventional diesel or gasoline generator, and a battery bank. First, the impact of charge controller operation and coulombic efficiency was studied through a comparative analysis of both the model presented in this paper and another that does not offer the ability to consider the charge controller operation or the relation between coulombic efficiency and the state of charge. The results show a difference between the models of approximately 33% in the number of hours of operation of a conventional generator, 31% in fuel consumption, and 31% in net present cost for hybrid power system configurations with low storage capacity. However, these differences were reduced when the capacity of the battery bank was increased because the charge currents were reduced, the acceptance of charge by the battery bank was improved, and the effect of the charge controller was minimised. Finally, a sensibility analysis was carried out for different sizes of battery banks, obtaining uncertainty in the net present cost, which depends on fuel cost and uncertainties about the battery bank's lifetime.

1. Introduction

Stand-alone hybrid power systems are useful for satisfying energy demands in remote areas that do not have access to electricity by tapping local resources. This fact has promoted the development of several approaches to modelling and sizing hybrid power systems. In the following discussion, the most relevant developments on this topic are reviewed and commented on.

There are several computational tools for simulating and/or optimising stand-alone hybrid power systems.

HOMER [1] is a frequently used computational tool for hybrid power system design that tests all possible combinations to determine the system configuration that minimises the net present cost over the lifetime of the hybrid system. HOMER can analyse hybrid power systems with photovoltaic (*PV*) panels, wind turbines, small hydropower, biomass power, lead acid batteries, diesel generators, fuel cells, and hydrogen storage.

HOGA [2,3] is a computer program for optimal sizing of hybrid power systems that can analyse systems with wind turbines, photovoltaic panels, small hydropower, lead acid batteries, diesel generators, fuel cells, and hydrogen storage. This computational tool uses genetic algorithms to arrive at the optimal system, and it can consider the net present cost, energy not supplied, and CO_2 emissions as objectives in mono- or multi-objective optimisation.

Hybrid2 [4] is a computational program used to simulate hybrid power systems with renewable power sources, energy storage, dump loads, power converters, loads, and diesel generators.

New advanced methodologies have been developed during recent years for the sizing of hybrid power systems.

Boonbumroong et al. [5] applied particle swarm optimisation (PSO) with a constriction coefficient algorithm to size a typical hybrid power system. This methodology was applied to size a hybrid system with *PV* arrays, wind turbines, a battery bank, and an inverter. The results were compared to the rule-of-thumb method and the HOMER program, resulting in the conclusion that the PSO with the constriction coefficient algorithm would considerably reduce the time required to find the optimal configuration.

Using the DIviding RECTangles (DIRECT) algorithm, Belfkira et al. [6] developed an optimisation model for hybrid wind/*PV*/diesel

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systems that minimised the total cost while covering the energy required. This methodology was implemented to design a hybrid system installed in Senegal; the results showed the influence of the load profile and renewable resources in the optimal configuration of hybrid systems, as well as the importance of the battery bank, which reduces the number of operating hours of the diesel generator and the total cost.

Recently, Kaldellis et al. [7] presented a study about electrification for remote consumers using *PV*-diesel hybrid systems with storage in a Greek island region of medium–high solar potential. The methodology consisted of analysing different combinations of *PV* panels, battery bank sizes, and diesel generator capacities, as well as calculating the long-term electricity generation cost for 10 and 20 years of operation, respectively. The results showed different optimal configurations when 10 and 20 years of operation were considered. These conclusions reveal the importance of using long-term data about renewable resources and probabilistic assessment in the design process. To that effect, Kaplani and Kaplanis [8] developed a stochastic simulation model for stand-alone *PV* systems that could also be adapted for a system with a diesel generator. The methodology proposed was subsequently implemented to design some *PV* systems installed in various European cities. The results were then compared with results obtained using a conventional methodology. The proposed stochastic *PV* sizing methodology suggested a 37% reduction in peak power of the *PV* generator and battery storage capacity compared to the conventional methodology. Similar results were found by Távora et al. [9], who presented a comparative study of deterministic and probabilistic approaches to the design of *PV* systems. Those results showed that the deterministic method could oversize the system.

Karaki et al. [10] developed a methodology to estimate the production costs of a wind–diesel system. A wind farm model was built using the joint probability distribution function of the total available wind power, while the diesel generator model was obtained using convolution methods. The production costs associated with the diesel system were estimated using the expected energy not supplied and a de-convolution process in reverse economic order.

Giannakoudis et al. [11] presented a model for optimisation and power management under uncertainty of hybrid systems with hydrogen storage, adapting the simulated annealing algorithm to consider uncertainty (stochastic annealing). The variables under uncertainty were solar radiation, wind speed, and the efficiencies of the electrolyser and fuel cell. The objective function considered was the net present value of investment over the lifetime of the system.

Tan et al. [12] developed a methodology for stochastic sizing of a battery bank in an uninterruptible power system with a photovoltaic generator using a Monte Carlo simulation approach. In this methodology, a random event was first generated, including a load profile, weather conditions, and failure; then, the required energy capacity was calculated. This process was repeated a number of times. Then, the results were statistically analysed using the cumulative distribution function and battery capacity at a determined confidence level that had been economically evaluated.

Moharil and Kulkarni [13] presented a methodology using the Monte Carlo simulation technique to consider the reliability of photovoltaic systems with diesel generators and battery storage.

In addition, several studies have shown the importance of storage batteries to reducing the operating hours of diesel generators and total net present cost [6,14,15]. Charge controller operation and coulombic efficiency have an important influence on the acceptance of the charge of the battery bank and consequently on the ability of the system to meet the energy demand. However, these factors are not considered in many studies and simulation models [1–4]. Finally, it is important to note that the use of long-term data and the consideration of uncertainty of the potential of renewable resources in the simulation and optimisation processes are determining factors in the optimal sizing of hybrid systems [8,9].

Considering the findings of the above literature review, the research work presented in this paper uses a mathematical model for hybrid systems that includes the aspects that have usually not been considered by other researchers. The model used was previously [16] developed by the authors. In this way, the influence of the charge controller and coulombic efficiency in the performance of a typical *PV*/wind/diesel/battery system is analysed. Specifically, this paper studies the joint effect of these parameters on the fuel consumption of the system and, consequently, on the net present cost. In addition, a sensibility analysis using a probabilistic model based on a Monte Carlo simulation approach shows the effect of uncertainty related to fuel prices and performs an estimation of the effect of battery bank lifetime on uncertainty with regard to the net present cost.

This work is presented as follows:

- The *PV*/wind/diesel/battery system model;
- Stochastic modelling of the renewable resources;
- The case study;
- Conclusions.

2. The PV/wind/diesel/battery system model

Fig. 1 shows the hybrid power system used to develop the work presented in this paper. The system only has AC loads, and the inverter connects the lead acid battery bank, the wind turbine, and the photovoltaic generator to the AC bus. The model of this system has been presented in previous papers of the authors [16,17]. Next, the most relevant aspects of this model are described.

2.1. Photovoltaic panel model

The output power (P_{PV}) and efficiency (η_{PV}) can be estimated using Eqs. (1) and (2) [18].

$$P_{PV} = AG\eta_{PV} \quad (1)$$

$$\eta_{PV} = \eta_{STC}[1 + \alpha(T_c - 25)] \quad (2)$$

where A is the area of the panel in m^2, G is the incident solar radiation in W/m^2, η_{PV} is the efficiency in a determined operating condition, η_{STC} is the efficiency under standard test conditions (*STC*), T_c is the cell temperature in degrees C, and α is the temperature coefficient in% per degree C. Combining Eqs. (1) and (2), it is possible

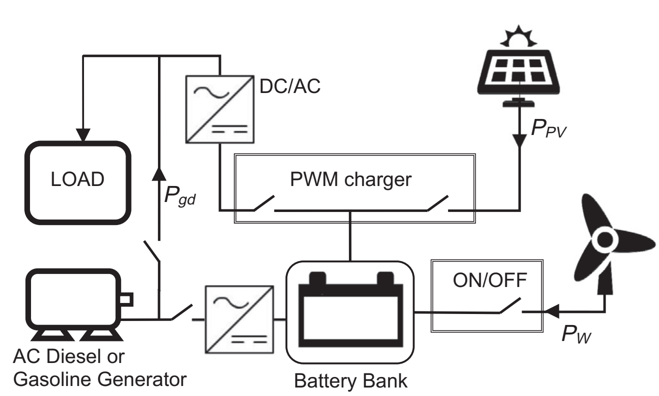

Fig. 1. Hybrid power system.