Energy Conversion and Management 134 (2017) 167–177

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Daily operation optimisation of hybrid stand-alone system by model predictive control considering ageing model

Rodolfo Dufo-López [a,*], L. Alfredo Fernández-Jiménez [b], Ignacio J. Ramírez-Rosado [a], J. Sergio Artal-Sevil [a], José A. Domínguez-Navarro [a], José L. Bernal-Agustín [a]

[a] Department of Electrical Engineering, University of Zaragoza, Calle María de Luna, 3, 50018 Zaragoza, Spain
[b] Department of Electrical Engineering, University of La Rioja, Logroño, Spain

ARTICLE INFO

Article history:
Received 18 September 2016
Received in revised form 13 December 2016
Accepted 14 December 2016

Keywords:
Hybrid renewable standalone systems
Battery
Diesel generator
Predictive control
Optimisation
Ageing models

ABSTRACT

This article presents a method for optimising the daily operation (minimising the total operating cost) of a hybrid photovoltaic-wind-diesel-battery system using model predictive control. The model uses actual weather forecasts of hourly values of wind speed, irradiation, temperature and load. Five control variables are optimised, and thus their optimal set points values determine the optimal control strategy for each day. This involves the use of an accurate model for estimating the degradation of the batteries by considering the capacity loss due to corrosion and degradation. The model considers the extra costs of maintaining and replacing the diesel generator due to running out of its optimal conditions. The optimisation is carried out by means of genetic algorithms. An example of application compares the total operating cost obtained using the optimal control strategy for each day with the cost of using the optimal control strategy found for the whole year, obtaining savings of up to 7.8%. Also the comparison with the cost of using the "load following" control strategy is analysed, obtaining savings of up to 37.7%.

1. Introduction

In many cases, standalone systems (off-grid systems) for energy supply are more cost-effective than building new power lines to supply those consumers energy from a power distribution grid [1]. Hybrid standalone systems, which use more than one energy source, are usually better from an economic point of view than standalone systems that only use one energy source [2]. Photovoltaic (PV) generators with lead-acid battery storage are the technologies most widely used in small standalone systems [3]. Hybrid PV-diesel-battery systems are also widely used, as they are usually cost-effective (for any size or power) compared to diesel-only systems [4]. Also, they can be cost-effective compared to PV-only systems in areas where solar irradiation is much lower in winter than in summer [5]. Moreover, in these areas, the PV-diesel-battery system usually has lower life cycle emissions than non-hybrid systems [6]. In areas with high wind speeds, wind-diesel-battery, PV-wind-battery or PV-wind-diesel-battery systems can be cost-effective [7]. The control of a hybrid standalone system is usually carried out using a bidirectional inverter [8] (also called bidirectional converter or inverter/charger).

Controlling the system includes managing the battery by preventing over-charge or over-discharge to maximise the battery's lifetime and managing the start/stop of the DG. Many inverter/chargers include state of charge (SOC) control, which calculates the SOC of the battery bank. They disconnect the battery from the load when a minimum SOC setpoint is reached and reconnect it after it achieves a specified higher value of SOC. Controllers can implement different strategies, most typically [9] the load following (LF) strategy, which determines that the DG operates just enough to meet the net load (that is, the DG only supplies the net load when the battery bank cannot), and the cycle charging (CC) strategy, which establishes that the DG runs at rated power when the batteries cannot meet the net load not only to meet the demand but also to charge the batteries until a specified SOC is reached.

This article contains a method for optimising the daily operation of a hybrid PV-wind-diesel-battery standalone system (Fig. 1). The objective is to minimise the total operating cost of the standalone system for each day using a model predictive control (MPC) scheme. MPC utilises predictions of the hourly load and actual hourly weather forecasts for wind speed, irradiation and temperature based on numerical weather prediction (NWP) models. A computer tool has been developed for simulating the expected performance of the hybrid system (using past data and

* Corresponding author.
E-mail address: rdufo@unizar.es (R. Dufo-López).

http://dx.doi.org/10.1016/j.enconman.2016.12.036
0196-8904/

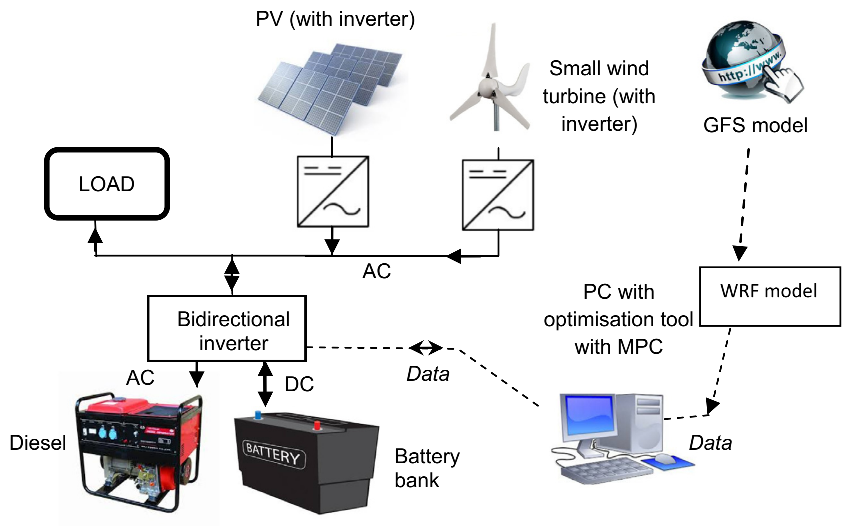

Fig. 1. PV-wind-diesel-battery system (AC coupled).

current-day forecast data) and optimising the operation of the standalone system (by minimising its total operating cost during the day). The NWP model used in this paper is the Weather Research and Forecasting (WRF) model [10], which gets data from a global forecasting system (GFS) model [11].

Each day, before 12:00 a.m., the computer tool is fed with actual local hourly weather forecasts as well as forecasts of hourly load. Then it optimises the control strategy for that day (24 h), sending the control set points to the bidirectional inverter.

This article is structured as follows. Section 2 presents the literature review and research gaps. Section 3 shows the method for optimising the system daily operation, including the description of the control variables which set points must be optimised, the mathematical models of the components of the hybrid PV-wind-diesel-battery standalone system to perform the simulations, the economic calculation of the total cost of operating this hybrid system for one day and the genetic algorithm (GA) used in the optimisation. Section 4 includes the results and discussion of the optimisation, using the MPC for several days as a case example. Conclusions are shown in Section 5.

2. Literature review

Several reviews of works related to hybrid standalone systems have been published. Bajpai and Dash [12] presented a review of the most relevant works related to this kind of system. Mohammed et al. [13] published a complete review in the same way. Nema et al. [14] highlighted the current and future state-of-the-art hybrid PV-wind systems. Mohammed et al. [15] reviewed the state-of-the-art hybrid PV-diesel-battery system control strategies. Typical LF and CC strategies were used in many prior works. Dufo-López et al. [16] demonstrated the optimisation of design and control strategies (for a whole year) for PV-diesel-battery systems using the LF strategy, the CC strategy and a combined strategy. Ameen et al. [9] presented MATLAB simplified performance models of PV-diesel-battery systems using LF and CC strategies. Maatallah et al. [1] optimised a PV-wind-diesel-battery system using HOMER commercial software and compared the LF and CC strategies, showing that the LF strategy implies a lower net present cost. Bortolini et al. [5] used the LF strategy to integrate PV and batteries in a diesel-based system. On the other hand, Upadhyay and Sharma [17] used the CC strategy to optimise a PV-hydro-biomass-bio gas-diesel-battery system. In an earlier work, Dufo-López et al. [18] presented a novel strategy using GA to optimise up to 12 control variables to be applied in a general PV-wind-hydro-diesel-hydrogen system. They optimised the control variables to minimise the net present cost—that is, to minimise the operational cost of a whole year—thus obtaining set points for the control variables to be used for the whole year. In all these studies, the control strategies were evaluated over long periods typically lasting one year. In other studies, researchers have demonstrated daily optimisation (minimising the total operating cost for 24 h). Kusakana [19] evaluated two control strategies for minimising the daily operational cost of a PV-diesel-battery system: “continuous” (similar to the LF strategy) or “On/Off” (similar to the CC strategy) operation of the DG. Ashari and Nayar [20] optimised dispatch strategies for operating a PV-diesel-battery system by obtaining the optimal set points for starting and stopping the DG, the battery charger and the maximum power of the DG and the charger with the objective of minimising the overall system costs. Tazvinga et al. [21] used the LF strategy in a PV-diesel-battery system and gave an accurate estimation of the daily diesel fuel cost and how much they saved in relation to the cost of a diesel-battery system. Balamurugan and Kumaravel [22] generalised an algorithm to optimise the operation of hybrid power systems by shedding non-priority loads when the available energy sources and energy storage cannot meet the whole load. Muselli et al. [23] put forth a method of optimally sizing PV-diesel-battery systems with two battery charge threshold parameters to start and stop the DG. Baghadi et al. [24] optimised a PV-wind-diesel-battery standalone system in Algeria that included a mathematical model to ensure efficient energy management on the basis of LF strategy. Bortolini et al. [5] optimised a PV-diesel-battery system designed to minimise both the levelised cost of the electricity and the carbon footprint of energy using the LF strategy. Moghavvemi et al. [25] showed a hybrid PV-diesel system for supplying remote-controlled FM transmitters in remote locations, including applications for sensing, managing, controlling and using the CC strategy. Merei et al. [26] presented a method for modelling and optimising a PV-wind-diesel-battery system using batteries of lithium-ion, lead-acid, vanadium redox-flow or a combination. The battery control included different battery operating points and ageing mechanisms.

Few works use an MPC to optimise the operation of hybrid standalone systems. Al-Alawi et al. [27] presented an MPC applied to a PV-diesel-battery system to supply water and power using an