Energy Conversion and Management 106 (2015) 479–494

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Hybrid wind–photovoltaic–diesel–battery system sizing tool development using empirical approach, life-cycle cost and performance analysis: A case study in Scotland

Leong Kit Gan *, Jonathan K.H. Shek, Markus A. Mueller

Institute for Energy Systems, School of Engineering, The University of Edinburgh, The King's Buildings, Mayfield Road, Edinburgh EH9 3DW, UK

ARTICLE INFO

Article history:
Received 27 May 2015
Accepted 10 September 2015

Keywords:
Hybrid wind–photovoltaic–diesel–battery system
Off-grid
Standalone
Isolated
Optimum sizing
Energy cost
Renewable energy
Modelling

ABSTRACT

The concept of off-grid hybrid wind energy system is financially attractive and more reliable than stand-alone power systems since it is based on more than one electricity generation source. One of the most expensive components in a stand-alone wind-power system is the energy storage system as very often it is oversized to increase system autonomy. In this work, we consider a hybrid system which consists of wind turbines, photovoltaic panels, diesel generator and battery storage. One of the main challenges experienced by project managers is the sizing of components for different sites. This challenge is due to the variability of the renewable energy resource and the load demand for different sites. This paper introduces a sizing model that has been developed and implemented as a graphical user interface, which predicts the optimum configuration of a hybrid system. In particular, this paper focuses on seeking the optimal size of the batteries and the diesel generator usage. Both of these components are seen to be trade-offs from each other. The model simulates real time operation of the hybrid system, using the annual measured hourly wind speed and solar irradiation. The benefit of using time series approach is that it reflects a more realistic situation; here, the peaks and troughs of the renewable energy resource are a central part of the sizing model. Finally, load sensitivity and hybrid system performance analysis are demonstrated.

1. Introduction

Lack of affordable and reliable electricity supply is a major impediment to the development of many rural communities, particularly those remote from the existing electricity grid. This is especially true in developing countries, where off-grid systems are often the only practical solution for electricity generation. Traditionally, off-grid systems rely solely on diesel generators, but a significant rise in oil prices has made diesel-based systems uneconomic. Recent developments in renewable generation technologies allows the use of natural resources (wind, hydro, or photovoltaic (PV)) as alternative energy sources, but their intermittency typically results in inadequate energy supply for a substantial proportion of the year. However, combining renewable energy sources (RES) with conventional diesel generation and energy storage systems in so called "hybrid renewable energy systems" may provide reliable electricity supply with reduced battery storage and/or diesel requirements. A fossil fuel-based generation is suggested to be incorporated into the system rather than solely increasing the wind turbine or PV sizes excessively to cope with the worst month [1]. Moreover, the utilisation of two or more RES is economically beneficial especially for locations whereby weather changes significantly across seasonal variations [2]. In addition, it has been studied that due to the high initial cost of the system, government subsidy is necessary to adopt the system on a large scale basis in the remote areas [3]. Even though the cost of electricity generated from most of the hybrid energy systems are higher than that of the national grid electricity tariff, the cost of national grid extension to these remote areas are difficult and uneconomical [4].

Several literatures have studied the sizing of hybrid energy systems. Earlier work [5] simply shows the generation capacity is determined to best match the power demand by minimising the difference between total power generation and load demand over a period of 24 h. The author iteratively optimised the components by using hourly average data of wind speed and solar irradiation in meeting a specific load demand. In [6], the authors further utilised linear programming technique to optimise the sizing of the hybrid system components (battery capacity and diesel fuel usage) within the 24 h period. Kaldellis et al. [7] pointed out that focusing on the

* Corresponding author. Tel.: +44 (0)131 650 5629.
E-mail address: L.Gan@ed.ac.uk (L.K. Gan).

http://dx.doi.org/10.1016/j.enconman.2015.09.029
0196-8904/© 2015 The Authors. Published by Elsevier Ltd.

installation cost is insufficient for a hybrid system sizing methodology which is based on simplified cost analysis. Operation and maintenance (O&M) costs take up a large proportion of the overall cost of the system over its lifetime. Thus, Kaldellis has developed a method to calculate long-term energy-production cost for a wind–diesel hybrid system by taking into consideration fixed and variable costs of maintenance, operation and financing, and initial costs. Alternatively, the authors in [8] have developed an algorithm to optimally size a standalone hybrid wind–diesel system by considering the total system reactive power balance condition. In another mean of selecting the optimal combination of a hybrid renewable energy system to meet the demand, evaluation was conducted on the basis of reliability of the system by considering the loss of load probability (LOLP) [9]. The LOLP sensitivity analysis on total installation cost has been demonstrated in [10] for the considered hybrid system. In a different perspective, the authors in [11] described an optimal energy storage sizing method by considering the compensation cost of wind power and load curtailment.

In this work, a tool specifically for sizing off-grid hybrid renewable energy systems has been developed. The main feature of this tool is to assists project managers to visualise and evaluate the trade-offs between batteries and diesel generator usage, given a site specific resource availability and load demand. As far as the author is aware, other hybrid system sizing tools do not have the capability of demonstrating their results with the proposed approach. The process of seeking the optimum configuration is demonstrated graphically which allows the hybrid system developer to understand the sizing methodology and trade-offs in a system. Similar graphical approach has been adopted in [7,12] as part of their result's analysis, however it has not been used on analysing the trade-offs between batteries and diesel generator usage. In this paper, the methodology of sizing the hybrid system which considers financial viability and technical performances are outlined. The hybrid system components and life-cycle cost modelling utilised in this work are first explained. In particular, the wind turbine and solar panel are represented mathematically with their coefficients obtained empirically from the measured wind speed, solar irradiation and their respective output power data. Then, the optimum configuration of a hybrid system is obtained based on minimum life-cycle cost. It is then followed by the load sensitivity towards the cost and the overall performance of the hybrid system. The corresponding sensitivity analysis on batteries and diesel generator utilisation throughout the year are shown as part of the discussion.

2. Modelling of hybrid system components

As mentioned before, a graphical user interface (GUI) has been developed which assists the project manager to analyse the long term costs of energy production of a hybrid system. This potentially helps developers to make a justifiable components sizing decision by taking into consideration of the financial, renewable resources and technical factors. Fig. 1 shows the block diagram of the proposed hybrid system implemented in this work. The power flow directions are indicated with the arrows. In this research, the wind turbine and the PV systems are modelled using empirical data, which directly correlates the relationship between renewable resources and generated power output. Thus, the losses of the system are accounted in the equation. Similarly, the efficiency of the diesel generator is related by its power output and its fuel consumption. The modelling approach of these systems will be further described in the following sections. For the case of the grid-forming inverter, it is assumed that it has an average operational efficiency of 95%. The widely employed lead-acid batteries are considered in this study. Lead-acid batteries typically have coulombic (Ah) efficiencies of around 85% and energy (Wh) efficiencies of around 70% over most of the state of charge (SOC) range [13]. These parameters are determined by the details of design and duty cycle to which they are exposed [13]. In the following case studies, a round-trip efficiency of 70% is adopted.

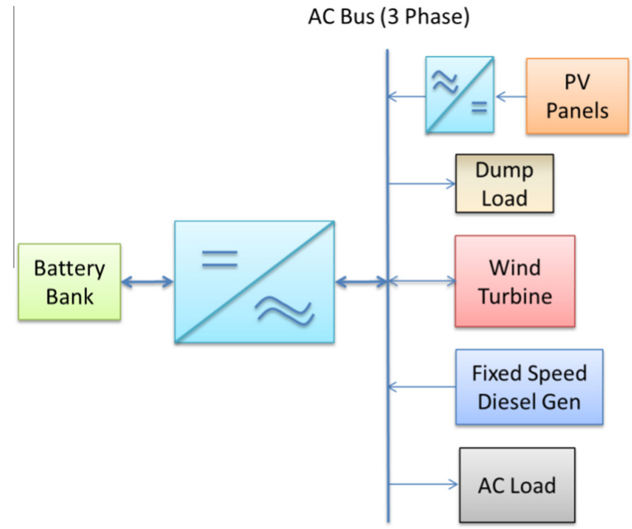

Fig. 1. Proposed hybrid wind–PV–diesel system.

The layout of the GUI is demonstrated in Fig. 2. The load profile, amount of wind turbines and PV panels, battery parameters, inflation and discount rate, cost of components, and wind turbine and PV panel coefficients can be altered before performing life-cycle cost simulation. In addition, the user is able to load yearly renewable resources such as wind speed and solar irradiation for the interested site. In order to simplify matters, the renewable energy resources and load are assumed to be same throughout the 20 years lifetime. With all the information given to the GUI programme, the optimal batteries and diesel generator sizes are sought. The following subsections describe the modelling of the system components, such as the wind turbine and PV panels, and also load profile and system operation modelling.

It is important to note that the developed sizing tool is generic and it is suitable to be used for different types of wind turbines and solar panels. In addition, generalise wind turbine and solar system power curves can be used if needed. This can be achieved by keying in the particular power curve's coefficients within the GUI. However, the author has adopted a Gaia-Wind wind turbine and Sanyo solar panels as an example in this work due to the data availability on both systems. The modelling approach and analysis carried out in the following sections can serve as a reference and can be modified to suit any other systems of interest.

2.1. Wind energy modelling

As stated before, the renewable energy conversion systems (wind and PV) is represented with the power curve's coefficients. For the case of wind energy systems, most of the small wind turbine manufacturers do provide their wind turbine power curves as part of the associated data sheets. By plotting an estimated power curve and interpolating it with a polynomial equation, the coefficients can be obtained. Higher resolution power performance data are published and readily available if the wind turbines are accredited by certification body such as TUV NEL, Small Wind Certification Council (SWCC) and National Renewable Energy Laboratory (NREL).