Renewable Energy 99 (2016) 919–935

Contents lists available at ScienceDirect

Renewable Energy

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

Stochastic-heuristic methodology for the optimisation of components and control variables of PV-wind-diesel-battery stand-alone systems

Rodolfo Dufo-López [a, *], Iván R. Cristóbal-Monreal [b], José M. Yusta [a]

[a] Electrical Engineering Department, University of Zaragoza, Calle María de Luna, 3, 50018, Zaragoza, Spain
[b] Centro Universitario de la Defensa, Academia General Militar, Ctra. de Huesca s/n, 50.090, Zaragoza, Spain

ARTICLE INFO

Article history:
Received 18 January 2016
Received in revised form
19 July 2016
Accepted 27 July 2016

Keywords:
Renewable stand-alone systems
Battery
Control variables
Monte Carlo simulation
Correlated Gaussian random variables
Genetic algorithms

ABSTRACT

In this paper a new stochastic-heuristic methodology for the optimisation of the electrical supply of stand-alone (off-grid) hybrid systems (photovoltaic-wind-diesel with battery storage) is shown. The objective is to minimise the net present cost of the system. The stochastic optimisation is developed by means of Monte Carlo simulation, which takes into account the uncertainties of irradiation, temperature, wind speed and load (correlated Gaussian random variables), using their probability density functions and the variance-covariance matrix. Also the uncertainty of diesel fuel price inflation rate was considered. The heuristic approach uses genetic algorithms to obtain the optimal system (or a solution near the optimal) in a reasonable computation time. This methodology includes an accurate weighted Ah-throughput battery model with several control variables, which can be set in the modern battery controllers or inverter/chargers with State of Charge control. A case study is analysed as an example of the application of this methodology, obtaining the stochastic optimisation an optimal system similar to the one obtained by the deterministic optimisation. It is recommended to perform first the deterministic optimisation (with low computation time), then the search space should be reduced and finally the stochastic optimisation can be obtained in a reasonable computation time.

1. Introduction

A very important factor for the sustainable development of human society is the access to electricity. However, nowadays electricity is still not accessible for 1,200 million people [1] due to the lack of electricity grids in remote areas of developing countries. In developed countries, there is also a need of electricity in remote locations (telecom stations, farms, mountain refuges, etc.) far from the electrical grid. In many remote locations, stand-alone systems (off-grid systems) are more cost-effective than extending a power line to the electricity grid. In some cases hybrid stand-alone systems (using more than one source of energy) are more cost-effective than systems that use a unique energy source. The most widely energy source used in stand-alone systems is photovoltaic (PV), combined with battery storage. In areas where solar irradiation is much lower in winter than in summer, hybrid PV-diesel-battery systems can be cost-effective. In areas with high wind speed, the optimal system is usually a hybrid PV-wind-battery or a PV-wind-diesel-battery system.

The optimisation of the stand-alone systems, i.e., the minimisation of the net present cost of the system (NPC, which includes all the costs throughout the lifetime of the system, which are converted to the initial moment of the investment using the effective interest rate, according to standard economical procedures) is very important as the user usually want to choose the lowest cost system.

The optimisation of this kind of systems is usually carried out using a deterministic approach, i.e., considering that the electrical load and the meteorological data (irradiation, temperature and wind speed) do not vary during the years, i.e., the performance of one year can be extrapolated to the rest of the years of the system lifetime (which is usually considered to be 25 years or more). The cost of the diesel fuel is usually considered as a fixed cost during the system lifetime, or, in the best case, a fixed annual inflation for the diesel fuel price is taken into account.

However, the performance of the real system is different from one year to another one, as load and meteorological variables are different. Also, the cost of the diesel fuel consumed each year

* Corresponding author.
E-mail addresses: rdufo@unizar.es (R. Dufo-López), icristob@unizar.es (I.R. Cristóbal-Monreal), jmyusta@unizar.es (J.M. Yusta).

http://dx.doi.org/10.1016/j.renene.2016.07.069
0960-1481/

depends on the actual price of the fuel of each year. These are the motivations to perform in this paper a probabilistic optimisation of stand-alone systems. The stochastic approach will allow to consider the different performance of the system during the years of its lifetime, considering the uncertainties of meteorological variables and load, and its correlations, and it will also allow to consider the uncertainty of the diesel price fuel. The designer will obtain probability functions for the variables of the results (expected cost, lifetime of the battery bank,…), knowing the mean, standard deviation, minimum and maximum expected for each of the results and therefore having much more information than using the deterministic approach.

Also, the optimisation of this kind of systems is usually done using simple battery models, which can imply an estimation of the battery storage lifetime much higher than the real battery lifetime. In this work an accurate model for the estimation of the battery lifetime is used.

This paper is structured as follows. Section 2 shows the literature review and research gap. Section 3 shows the methodology of the optimisation, including the variables involved in the optimisation and the mathematical models of the components of the system. Section 4 shows an example of application and section 5 shows the main conclusions.

2. Literature review and research gap

Many previous studies have examined the performance and the optimisation of the electrical supply of stand-alone systems, usually PV panels and/or wind turbines and/or diesel generators with battery storage. Reviews of relevant works related to stand-alone hybrid systems can be found in Refs. [2–4]. A comparative study of stand-alone hybrid solar energy systems is shown in Ref. [5]. Reviews of the software tools used for the optimisation of hybrid systems are shown in Refs. [6,7]. The optimisation of PV-wind systems is discussed in Ref. [8] while a review of relevant papers of optimisation of stand-alone systems is shown in Ref. [9]. A novel optimisation method for stand-alone PV systems was recently shown in Ref. [10]. In Ref. [11] the energetic and economic optimisation of a PV system (with battery storage) is shown. A methodology based on levelized cost of supplied and lost energy for the design of stand-alone systems is shown in Ref. [12]. Previous relevant works of the authors of this work related to the optimisation of hybrid stand-alone systems can be found in Refs. [13–15].

In some cases the stand-alone system does not include battery storage [16], but storage is needed (and cost-effective) in most of the off-grid applications. In most of the previous works, the optimisation tries to obtain the combination of components (and/or, in some cases, of control strategies), which minimises the NPC, the levelised cost of energy (LCE, calculated as NPC divided by the total energy consumed by the load during the lifetime of the system) or the operation cost of a short interval. Some of these works use heuristic techniques, like genetic algorithms (GA) [17,18] in the optimisation. A recent application of GA in the optimisation of hybrid stand-alone systems is shown in Ref. [19]. In Ref. [20] a meta-heuristic algorithm (Cuckoo Search) is applied in the optimisation of hybrid stand-alone systems. Other works consider several variables to be minimised, usually LCE, CO_2 emissions and unmet load or loss of power probability, most of them using Pareto-optimisation techniques as multi-objective evolutionary algorithms (MOEA's) [21–23].

The optimisation in previous studies was usually carried out using a deterministic approach, although some previous studies used a stochastic approach, taking into account the uncertainties in renewable sources.

In Refs. [24], Paliwal et al. show a probabilistic model for battery-storage systems to facilitate the reliability assessment of stand-alone renewable systems. They compare with Monte Carlo simulation (MCS), obtaining better results with their probabilistic model. However, in this work the battery lifetime estimation is not obtained and no optimisation is performed.

Arun et al. [25] optimised a PV-battery system using MCS, including the uncertainty of solar irradiation. Kamjoo et al. [26] showed a method based on chance-constrained programming (CCP) for the optimisation of a PV-wind-battery system, including the uncertainties in wind speed and irradiation. In Refs. [27], Kamjoo et al. use GA in the multi-objective optimisation of PV-wind-batteries systems, considering uncertainties by means of CCP and comparing the results with MCS. Maheri [28] evaluates the reliability of different PV-wind-diesel-battery systems obtained by deterministic design, and later [29], uses two algorithms (with MCS) in the optimisation of the margin of safety.

Recently, Alharbi and Raahemifar [30] presented a stochastic model for the coordination of distributed energy resources in an islanded microgrid, considering the uncertainties of load, wind and irradiation. Chang and Lin [31] also considered the uncertainties of load, wind and irradiation and proposed the optimal design of hybrid renewable energy systems using MCS with simulation optimisation techniques (stochastic trust-region response-surface method). The effect of the uncertainties in the economics of renewable grid-connected generators have been studied in Refs. [32], where Falconett and Nagasaka show a probabilistic model to evaluate the effects of different support mechanisms (governmental grant, feed in tariff and renewable energy certificate) on the net present value of grid-connected small-scale hydroelectric, wind energy and solar PV systems. Tina and Gagliano [33] studied the impact of the tracking system on the probability density function (PDF) of the power produced by the PV system while Pereira et al. [34] used MCS in risk analysis in small renewable systems.

All the previous works use a different stochastic approach and probabilistic models. However, some of them do not calculate costs (they do not perform the optimisation), most of them do not consider correlation between the input variables, others do not consider storage and others use simple classical Ah-battery models and simple models for the estimation of the batteries' lifetime.

The use of simple models for the batteries can imply a too optimistic estimation of the batteries' lifetime (several times the real lifetime [35]) and therefore, erroneous results for the NPC and the LCE, as the battery bank total cost (acquisition cost plus maintenance plus replacement at the end of its lifetime) is usually the system's highest cost [36]. The battery lifetime in the previous optimisation works has always been estimated in fixed values or by means of classical models (the number of equivalent full cycles or the cycle counting method). These classical models assume that operating conditions are the same as the conditions of the standard tests that battery manufacturers use to obtain the lifetime number of IEC (International Electrotechnical Commission) cycles (shown in the battery datasheet). Therefore, they can predict an overly optimistic battery lifetime, as Dufo-López et al. showed in Ref. [35], in which different ageing models for lead-acid batteries were compared and the Schiffer et al. weighted Ah-throughput model [37] was shown to obtain the most accurate results in terms of battery lifetime.

Also, none of the previous studies include the model of the PWM (pulse-width modulation) battery charge controller (or inverter/charger), and therefore, none consider the optimisation of the control variables, which can be set in the battery controller.

In the present paper, it is shown a new methodology for the stochastic-heuristic optimisation of stand-alone hybrid renewable systems (Fig. 1) considering the uncertainties of the input variables