Energy 52 (2013) 165–172

Contents lists available at SciVerse ScienceDirect

Energy

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

Components sizing of hybrid energy systems via the optimization of power dispatch simulations

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ARTICLE INFO

Article history:
Received 9 July 2012
Received in revised form
2 January 2013
Accepted 8 January 2013
Available online 27 February 2013

Keywords:
Hybrid energy system
Components sizing
Power dispatch
Electrification

ABSTRACT

A hybrid energy system comprising the diesel generator (DG), photovoltaic (PV) panels, and battery bank is well suited for installation as a decentralized power generation system for the electrification of remote rural households in the developing countries. This paper proposes a new methodology for the components sizing of hybrid energy system based on the optimization of the power dispatch simulations. The optimization of the power dispatch with the operation of hybrid system is implemented by minimizing the cost of energy (COE) with consideration to the capital depreciation cost, fuel cost, emissions damage cost and maintenance cost. A hybrid system applicable to Alaminos, Philippines was studied using the proposed methodology. The simulation results show that the proposed sizing search method can lead to the convergence of the optimal objective solutions with reduction to its computational load. Two sizing solutions for the hybrid energy system are presented. The optimized power dispatch schedules and cost compositions of COE are analyzed in detail.

1. Introduction

It is reported that there are currently around 1.4 billion people in the world who are lacking access to electricity [1]. This is expected to be a persisting problem for a long time and there could still be 1.2 billion people without access to electricity by 2030. Most of these people live in sub-Saharan Africa, India and other Asian developing countries (excluding China) [1]. Many of these "un-electrified" rural households are too remotely located to be viable for appropriate infrastructure installation that links them up with the main power network [2,3]. A simple and cost effective approach of electrifying these rural areas is to install an on-site (decentralized) power generation system. Currently, the diesel generator (DG) is the most commonly used generator for on-site power generation as it is relatively low in cost and easy to deploy. On the other hand, the disadvantages of using DG as a standalone power generation system are that it requires frequent maintenance, its operation is not energy efficient, its application is often restricted by the availability of diesel at its local venue of consumption, and that there is an additional variable overhead (depending on location) on the cost of the transportation of the diesel. Despite all these issues, DG is still widely adopted in such power generation systems as it is still relatively one of the most feasible means of achieving rural electrifications.

Taking advantage of the emergence of renewable sources, the hybrid system of DG/Photovoltaic (PV) with battery (BT) is deemed as one of the best solutions for the household electrification in rural areas of developing countries in terms of achieving a better balance between managing the operating cost, reducing carbon emissions, and improving the overall systems' reliability. Such kind of hybrid DG/PV power systems have been installed and tested throughout the world [4,5].

The objective of hybrid-system-sizing optimization is to find the optimal–size combination of the system components that can reliably supply electric power to a given load demand profile at a certain location with the lowest cost of energy (COE). The computation of the system COE takes into account the discounted equipment cost, running cost, emission damage cost, maintenance and replacement cost of the entire project lifecycle. Traditionally, the sizing approach for the hybrid system employs rule-of-thumb methods that are based on hardware expertise knowledge and experiences of the respective engineers [6]. Clearly, it is difficult to get the optimal design solution simply by using such rule-of-thumb methods due to the complexity of the problem and the highly nonlinear characteristics of the components in the system [7,8]. The criteria of optimum components sizing for a hybrid system may

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0360-5442/$ – see front matter
http://dx.doi.org/10.1016/j.energy.2013.01.013

differ according to each application concerned. For example, in [9], the so-called sustainability is taken as a criterion in its optimization objective. On the other hand, most of the reported methodologies for components sizing are developed based on the minimization of the cost and deficiency of the power supplies [10–12]. Quite a few software programs such as HYBRID2, DER-CAM, HOMER, RETScreen and HOGA etc. [8,13–17] have been developed for the techno-economic assessment of hybrid system performance. In these software tools, DER-CAM is particularly applied to the power dispatch operation of pre-defined hybrid/microgrid systems while HYBRID2 and RETScreen are applied in system detail designs and project techno-economic feasibility studies, respectively. Most of the existing models including HOMER and HOGA, neglect the components lifetime-reduction cost in the optimization of time-series operation control. In practical operation, the lifetime of some components (e.g. batteries) is highly dependent on its operation status (on, off and current flow intensity). Therefore, the components' lifetime-reduction cost has to be considered in the optimization of the operation plan. The optimization technique is also a subject that is widely investigated by researchers for the sizing of hybrid system. The approaches including the generic algorithm [18,19] and particle swarm optimization [20,21] are widely used in the component sizing for hybrid systems. Some other techniques such as linear programming [22], neural networks [23,24], simplex algorithm [25], iterative and probabilistic approaches [26–28] etc., have also been utilized in the case studies. For an overview of more optimization techniques, readers are referred to [29].

As the components sizing and system operating control are interdependent [16,17], the approach proposed in this work performs the optimization of the hybrid system sizing design by simulating the operation plan. The system components lifetime-reduction costs associated with the operation status are included in the developed model. Usually, genetic algorithms are selected to be the optimization search method since they are highly applicable to nonlinear problems [7,8,16–19,30]. However, the computational load of genetic algorithms increases significantly with increasing hybrid system complexity or time-series resolution. A new random search method that offers a near-optimal solution with a more efficient optimization algorithm, is proposed in this paper.

2. Mathematical model

Fig. 1 shows the schematic configuration of a DG/PV hybrid system. In this system, the DC energy resources are integrated to the AC bus through individual power electronic inverters. The bi-directional inverter of the battery can charge/discharge the battery bank and also operates as a DC-AC converter. The scheme as shown in Fig. 1 is particularly suitable for the applications of hybrid system in rural area. It has very good expandability feature for covering the needs of growing energy and power demands [31]. In this work, this configuration is adopted as the case study example.

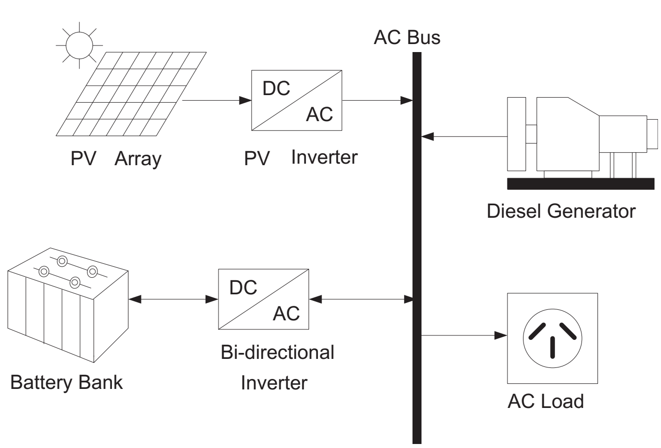

Fig. 1. A schematic configuration of a DG/PV hybrid system [31].

For a certain deployment location, the sizing optimization for a hybrid system design is to find the optimal size combinations of components that can cover the power demand in the given time range with the lowest COE. The COE is calculated from the summation of the capital depreciation cost (C^{dep}), fuel cost (C^{fue}), emissions damage cost (C^{dam}), and system maintenance cost ($C^{\mathrm{mai}}_{\mathrm{SYS}}$) in terms of the per kWh energy provided to the load demand during the time $[T_0, T]$. The cost calculation is based on the nominal cash flow. The mathematical formation of COE can be written as follows:

$$\mathrm{COE} = \frac{\sum_{k=1}^{M}\sum_{i=1}^{N}\left(C^{\mathrm{dep}}_{i,k}+C^{\mathrm{fue}}_{i,k}+C^{\mathrm{dam}}_{i,k}\right)+C^{\mathrm{dep}}_{\mathrm{BoP}}+C^{\mathrm{mai}}_{\mathrm{SYS}}}{\sum_{k=1}^{M}d_k} \tag{1}$$

where M and N are the number of discretized time intervals and distributed energy resources (DERs), respectively. The item $C^{\mathrm{dep}}_{\mathrm{BoP}}$ denotes the capital depreciation cost of system balance of plants (BoPs) including wires, controller, switch, and inverter, etc. The number of the discretized time interval is given by

$$M = \frac{T-T_0}{\Delta t} \tag{2}$$

As mentioned previously, the objective is to find the optimal DERs sizes and combinations that make COE minimum. The expression can be written as

$$\min\left(\frac{\sum_{k=1}^{M}\sum_{i=1}^{N}\left(C^{\mathrm{dep}}_{i,k}+C^{\mathrm{fue}}_{i,k}+C^{\mathrm{dam}}_{i,k}\right)+C^{\mathrm{dep}}_{\mathrm{BoP}}+C^{\mathrm{mai}}_{\mathrm{SYS}}}{\sum_{k=1}^{M}d_k}\right) \tag{3}$$

Normally, a typical load profile can be specified according to the measurements of history data or estimation from the load applications. We assume the total output of power can fully meet the load demand within each time intervals. The salvage values at the end of the hybrid system lifecycle for all DERs and system BoPs are assumed to be zero. Physically, all components have a limited lifetime and their performances are degraded with time. This is known as physical lifetime. Within the time interval Δt, the capital depreciation cost based on physical lifetime for a component is calculated by

$$C^{\mathrm{dep}}_{\mathrm{phy}} = \Delta t\frac{wc^{\mathrm{cap}}}{t_{\mathrm{phy}}} \tag{4}$$

where w is the size of DER. It has to be decided in the optimization computation. In addition, some of DERs lifetimes (e.g. batteries) are highly dependent on the operation status. In order to take this effect into account in the optimization program, we define another parameter known as the lifetime throughput. For a specific DER, the capital depreciation cost based on the lifetime throughput is given as

$$C^{\mathrm{dep}}_{\mathrm{run}} = p\frac{wc^{\mathrm{cap}}}{P_{\mathrm{life}}} \tag{5}$$

where p is the energy delivered by the DERs within the time interval Δt in the operation plan. P_{life} is the energy lifetime throughput with DERs. The units of w in Eq. (4) and Eq. (5) are kW, kWh and m^2 for diesel generator, battery and PV, respectively. The capital cost of PV normally is provided by \$ $\mathrm{kW_p^{-1}}$. In this case, the specific cost of PV based on per square meter is obtained by