Journal of Cleaner Production 71 (2014) 158–167

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

# Optimal sizing of hybrid power systems using power pinch analysis

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ARTICLE INFO

*Article history:*
Received 3 September 2013
Received in revised form
27 November 2013
Accepted 9 December 2013
Available online 19 December 2013

*Keywords:*
Power pinch analysis (PoPA)
Hybrid power systems (HPS)
Renewable energy
Sizing
Optimisation
Management

ABSTRACT

Hybrid Power Systems (HPS) consist of different renewable generators, which produce electricity from renewable energy (RE) sources required by the load. An optimal sizing method is the key factor to achieve the technical and economical feasibility of the HPS. Power Pinch Analysis (PoPA) method has been applied to set the guidelines for proper HPS sizing. Different scenarios for RE generators allow the designers to choose the best alternative for their systems. The scenarios considered are the reduction of (1) the size of the most expensive RE generator, (2) the size of generator with the most abundant RE sources available during the time interval with large electricity surplus and (3) the size of both the most expensive and abundant RE sources available during the time interval with large electricity surplus. The results show that the first option yields the minimum capital and operating costs and results in the lowest payback period for a given set of electricity targets.



## 1. Introduction

The growing global concerns on the depletion of energy resources, climate change and environmental emissions have become the key drivers to sustainable development. Reducing greenhouse gas emissions and mitigating global warming are becoming socially and economically pressing for nations across the globe (Georgakellos, 2012). Effective measures to prevent climate change include mitigating emissions from the power generation systems (Battaglini et al., 2009) and to accelerate the implementation of renewable energy (RE) sources as clean alternatives to fossil fuels in power generation and hybrid power systems (HPS). In the long run, application of RE sources can prove to be a smart economic strategy as it can provide an effective safeguard to the changing climate while enhancing energy security and efficiency (Purvins et al., 2011).

Different types of renewable energy generators have been installed in HPS to produce electricity to be supplied to the loads. The high fluctuations in time and output of many RE sources however makes them harder to be utilised efficiently in large power networks (Görbe et al., 2012). This can significantly affect the systems performance because electricity should be produced and supplied at the time when it is needed. An optimal sizing method is therefore vital to ensure a cost-effective utilisation of RE sources at the desired conditions. Higher investment cost results from the larger HPS sizes, while supply fluctuations for a particular load may occur due to smaller HPS sizes (Hocaoğlu et al., 2009). In order to obtain an optimum HPS, various sizing methods such as the simulation, graphical, iterative, probabilistic and artificial intelligence techniques can be implemented.

Software tools that are available for designing the HPS include Hybrid Optimization by Genetic Algorithm – HOGA (Bernal-Agustín and Dufo-López, 2009), energyPRO (Lund et al., 2009), RETScreen (Redpath et al., 2011) and Hybrid Optimisation Model for Electric Renewables – HOMER (Goodbody et al., 2013). A graphical approach for optimal HPS was introduced by Borowy and Salameh (1996) who proposed a methodology to calculate the optimum size of a battery bank and the photovoltaic (PV) array in a hybrid wind-PV system. The minimum cost of the system was used to calculate the optimum configuration for a given load and a desired loss of power supply probability (LPSP). The optimum sizing is achieved by constructing the curve that represents the relationship between the number of PV modules and batteries. Kaldellis et al. (2009) developed an optimum sizing methodology

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0959-6526/$ – see front matter 
http://dx.doi.org/10.1016/j.jclepro.2013.12.028

for stand-alone PV-battery systems according to the PV panels' number against battery maximum size curve. Application of the method on case studies shows that the minimum energy payback period is achieved whilst providing 100% energy autonomy for remote consumers. The concept of design space is applied by Bandyopadhyay (2011) to establish the optimum sizing of generators and storage for isolated power systems. Identification of the design space is done by constructing the sizing curve, which represents the minimum storage capacity for a given generator rating.

Application of iterative optimisation technique for HPS optimisation has been carried out by Kaabeche et al. (2011). They recommended an optimal sizing model based on an iterative technique to optimise the capacity of different components in hybrid PV/wind power generation systems using a battery bank. A two-stage iterative approach for distributed generation (DG) sizing was given by Rotaru et al. (2012). The time-dependent evolution of generation and load are taken into account in determining the pseudo-optimal DG sizing without violating any of the system constraints under any operating condition. Mohamed and Khatib (2013) recently proposed an optimisation method based on iterative simulation to optimally size a PV/wind/diesel generators with battery storage. The optimal sizes obtained are closely matched with the results calculated by HOMER software.

The probabilistic approach was presented by Tina and Gagliano (2011). The authors evaluate the long-term performance of hybrid solar-wind power systems using the probability density function (PDF) based on the convolution technique. Ould Bilal et al. (2013) incorporated the fluctuating nature of the resources as well as the loads by using the probabilistic technique. The presented method eliminates the need for time-series data in optimising the hybrid PV-wind-battery system in order to reach the best compromise between annual cost system (ACS) and the loss of power supply probability (LPSP).

Rajkumar et al. (2011) applied the artificial intelligence method namely Neuro-Fuzzy in optimising the HPS. The PV and wind systems are modelled with the Adaptive Neuro-Fuzzy System (ANFIS) and the results showed that low excess energy is achieved. Nasiraghdam and Jadid (2012) recommended a novel multi-objective artificial bee colony algorithm to investigate the distribution system reconfiguration and the optimal sizing of a hybrid energy system. The key parameters considered as the optimisation objectives include the total power loss, total electrical energy cost and total emission. The optimal capacity of individual components in a stand-alone hybrid generation system is decided using Adaptive Genetic Algorithm by Chen (2013). The proposed method appears to be useful in locating the global optimum for large nonlinear systems.

In this paper, the Pinch Analysis technique is applied to optimally size an HPS – see e.g. Klemeš and Varbanov (2013). Pinch Analysis has been, and is still widely applied for the optimal targeting and design for various resource networks. This is demonstrated by the recent publications e.g. heat (Torres et al., 2013), mass (Tay and Ng, 2012), water (Shenoy and Shenoy, 2013), carbon (Munir et al., 2012), property (Saw et al., 2011) and gas (Lou et al., 2013). Those papers declared that the Pinch Analysis has gained general acceptance by the public on its usefulness due to its simple insightful approaches that are either based on graphical or numerical techniques. The recent extension of Pinch Analysis for the design of power systems is employed in this paper. Power Pinch Analysis (PoPA) technique introduced by Wan Alwi et al. (2012) helps designers to determine the minimum targets for outsourced electricity as well as the amount of excess electricity. The (PoPA) technique has been further extended by Mohammad Rozali et al. (2013a) to include the losses analysis associated with power conversion, transfer and storage. The previous studies have been broadened in the current paper to set the feasible limits for the size of RE generators in the HPS and to determine the battery capacity. Three scenarios have been considered to allow the user to decide the choice of investment paths consisting of several combinations of RE technologies.

**Table 1**
Limiting power sources for Illustrative Case Study.

| Power source | | Time, h | | Time interval, h | Power source rating, kW | Electricity generation, kWh |
|---|---|---|---|---|---|---|
| AC | DC | From | To | | | |
| Wind | | 2 | 10 | 8 | 80 | 640 |
| Biomass | | 0 | 24 | 24 | 70 | 1680 |
| | Solar | 8 | 18 | 10 | 60 | 600 |

## 2. Methodology

This section describes the step-wise procedure to obtain the optimal sizing of an HPS. The Modified Storage Cascade Table (SCT) previously developed by Mohammad Rozali et al. (2013a) is applied for electricity targeting and allocation in the system before further detailed design is carried out to establish the optimal sizing of generators and storage systems. In order to obtain the cost-effective HPS with the minimum electricity targets, an Illustrative Case Study is used to demonstrate the sizing method. The studied system consists of wind turbine, biomass generator and PV modules as the power producer while the lead-acid battery functions as the power storage system. The sizing procedure is implemented as follows;

***Step 1***: Based on the meteorological data and the load demands of a location, the limiting power data is extracted (Mohammad Rozali et al., 2013b). The maximum capacity for all RE generators is initially assumed without considering the demand profiles. The total electricity generation (source) is obtained by assuming that all the RE sources available for the given sample day are converted to electricity after the generators efficiency is taken into account. Tables 1 and 2 tabulate the limiting power sources and demands for the Illustrative Case Study. The maximum sizes for the RE generators are 80 kW, 70 kW and 60 kW for wind, biomass and PV.

***Step 2***: The Modified SCT (Mohammad Rozali et al., 2013a) is used to obtain the electricity targets for the system. The step-wise construction of the Modified SCT is done as follows (see also Table 3a);

1) Column 1 lists the time interval for power sources and power demands in ascending order, while Column 2 gives the duration between two adjacent time-intervals.
2) The total sum of ratings for power sources and power demands for each time interval are given in columns 3 and 4. These values can be obtained from the Power Cascade Table – PCT (Mohammad Rozali et al., 2013b). The sources and demands for the AC and DC electricity are listed separately.

**Table 2**
Limiting power demands for Illustrative Case Study.

| Power demand appliances | | Time, h | | Time interval, h | Power demand rating, kW | Electricity consumption, kWh |
|---|---|---|---|---|---|---|
| AC | DC | From | To | | | |
| | Appliance 1 | 0 | 24 | 24 | 30 | 720 |
| Appliance 2 | | 8 | 18 | 10 | 50 | 500 |
| | Appliance 3 | 0 | 24 | 24 | 20 | 480 |
| Appliance 4 | | 8 | 18 | 10 | 50 | 500 |
| Appliance 5 | | 8 | 20 | 12 | 40 | 480 |