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Break-even analysis and optimization of a stand-alone hybrid system with battery storage for residential load consumption—A case study

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ABSTRACT

To assure a real penetration of the enormous intermittent and dispersed naturally renewable resources especially solar and wind, optimal sizing of hybrid renewable power generation systems provide evidence to be indispensable. A determinist technique has been developed to optimize the annual capital cost and the levelized cost of energy of a stand-alone hybrid generation system. Generation and storage units for three systems (wind, photovoltaic, and hybrid photovoltaic–wind turbine) are optimally sized in order to meet the annual load and minimize the capital annualized cost. A case study is conducted to analyze one hybrid project, which is designed to supply residential household located in Monastir city, Tunisia.

Contents

1. Introduction

One of the major challenges confronting users and designers of wind and solar energy systems is the casual, unpredictable nature of the energy sources [1]. In one hand, the photovoltaic (PV) stand-alone system is an expensive option and it depends on the variation of sunshine periods. In the other hand, the stand-alone wind energy conversion system can provide an utilizable energy in a portion of the time during the year due to high cut-in wind speeds which range from 3.5 to 4 m/s [2] and due to the significant fluctuations in the magnitude of wind speeds from 1 h to another throughout the year. Hence, a stand-alone solar energy or wind energy system properly cannot match the electricity demand of

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consumers due to the high monthly and seasonal variations and the unattended operation mode for extended periods of time. For example, in the winter seasons, the solar radiation is at its lowest level while the wind speed is usually at its highest level. Moreover, during the nights, solar energy cannot be utilized while the wind energy may be exploited efficiently. Hence, simultaneous utilization of multiple energy resources by combining solar and wind energy conversion systems enhances greatly the certainty of meeting load demands. The combined systems, called also hybrid of energy systems (HES), are becoming more and more attractive and being extensively used for substitution of fossil-produced energy, and eventually to decrease air pollution [2].

In reality, the electrical demand can be random that's why stand-alone HES may suffer from intermittent breakdown, which impacts its supply reliability. This may make the HES unreliable relatively compared to the traditional supplies of electrical energy. Therefore, the use of some energy storage devices seems so necessary to provide a high reliability and avoid gross overdesign of the solar and wind system [3,4]. Another advantage of the HES is the possibility to reduce the required energy storage capacity when one of the optimum combinations of photovoltaic and wind energy is used [5,6]. These devices store the excess of electricity demand and subsequently meet the load demand in shortage of HES. The conventional lead-acid battery is the most general energy storage device at the actual time [7]. Generally storage systems are very expensive and need to be reduced to their minimum possible storage size for a renewable energy system in order to be cost effective [8]. However, a hybrid solar–wind power system improves the overall energy output and reduces energy storage requirements [8].

The output generation of the PV and wind turbines depends on the wind speed and solar radiation variations, that's why the batteries are used to store the surplus energy produced and discharge it when the renewable sources are not available [9]. The converter operates at maximum power point tracking mode to extract the maximum possible energy, regardless of the variation in weather conditions. Various operating strategies can be used, depending on the wind and solar availability and the controller topology. For instance, when solar power is not available at night, wind and battery backup will be used to supply the load demand. Moreover, when the output power generated by the two sources and the stored power in the battery bank are insufficient to meet the load power consumption, DC backup generators can be used to increase the reliability of the system.

For any given load condition, an accurate sizing of PV, wind and battery lead to a successful operation of a hybrid energy system [10].

Hybrid power systems are mainly used in remote and rural locations where the cost of supplying power is high. Besides, the daily load profiles are an important parameter in the hybrid system design, as it characterizes the power demand that must be met by the available renewable sources and backups. As the renewable sources vary throughout the day, the excess power is stored and the batteries will act as auxiliary supply to meet the load demand.

Nevertheless, the hybrid energy system presents some problems due to its increased complexity in comparison with single energy systems. This complexity makes the evaluation of the hybrid energy systems more difficult. The solar radiation and wind speed being highly location dependent, the sizing of such hybrid systems requires comprehensive analysis of these variables for a given site in relation to the system cost for different combinations. Hence, it is very important to determine the levels of the energy resources at which the response achieves its optimum. The optimum design parameters depend on the objective function which could be either at its minimum or a maximum values. In this study, we aim to develop an interesting optimization method for a PV/wind hybrid energy system. The objective function has to depend on PV and wind turbine power output and battery capacity.

2. Inspiration and background

In the past, a several surveys [11,12] were based upon a particular scenario with a definite set of design values yielding the optimum solution. Unfortunately, a lot of last approaches provided the optimum solutions without the aptitude to supply a general appreciation about how the total system cost changes as a function of the parameters design size. Recently, numerous research groups have carried out the optimization of autonomous hybrid energy systems. Borowy and Salameh [13] proposed an algorithm to optimize a photovoltaic-array with a battery bank for a standalone hybrid PV/wind system basing on a long-term hourly solar irradiance and peak load demand data. Later, Borowy and Salameh [14] optimized a PV/wind system combined with a battery bank taking into account the cost of the PV modules and battery units. Markvart [15] constructed a graphic technique to optimize the size of the PV/wind energy system basing on the monthly average solar and wind energy values of the south of England. Bagul et al. [16] used the long term data of wind speed, irradiance and ambient temperature measured every hour during 30 years and the load specifications for a typical New England house. They proposed a technique to determine the optimum relationship between the number of PV panels and the number of required storage batteries for the stand-alone hybrid wind–photovoltaic system, to match a certain loss of power probability. Morgan et al. [17] enhanced the sizing and the optimization of the autonomous renewable energy systems by predicting the battery state of voltage (SOV) rather than its state of charge (SOC). In fact, the simulated algorithm permitted them to forecast the hybrid energy system performance as a function of battery temperature. Celik [18] used the long measured hourly weather data of eight years in order to make a techno-economic investigation and optimization of a PV/wind hybrid energy system basing on 1996 weather data from TyB site of Cardiff, UK. The performance of the HES was evaluated in terms of solar and wind energy fractions, battery storage capacity and system cost. Yang et al. [19] utilized an optimization approach basing on the loss of power supply probability (LPSP) model for a PV/wind hybrid system in order to assess its reliability. Mitchell et al.[1] used a heuristic model, based on seasonal averages of wind, solar and load consumption in order to optimize HES for both grid-connected and stand-alone applications. Their model was able to minimize capacity of batteries and stand-by energy import. Tina and al. developed probabilistic methods which incorporated the irregular nature of the resources and the electrical demand in order to eliminate the requirement for time-series data and evaluate the long-term performance of HES [20]. Ashok [21] suggested a model to minimize the life cycle cost of a hybrid energy system and proposed a general model to find an optimal combination of energy components for a usual rural society. Ekren [22] introduced the response surface methodology as a numerical tool to the size optimization of PV/wind hybrid energy system for a given time-varying hourly load demand that is assumed to be the electricity consumption of the global mobile communications station at Izmir Institute of Technology Campus Area, Urla, Turkey. The achieved simulation was based on the hourly mean solar radiation and wind speed data for the period 2001–2003 registered at the meteorological station of Izmir institute. The Response Surface Methodology, used by Ekren, led to a better understanding of the accurate relationship between input variables such as PV size, wind turbine rotor swept area and battery capacity, and output variables such as the hybrid energy system cost.