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Modelling autonomous hybrid photovoltaic-wind energy systems under a new reliability approach

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ABSTRACT

Hybrid photovoltaic-wind energy systems are being designed and implemented as stand-alone or grid connected generation systems, due to the need to use local, environmental friendly and low cost energy sources. In this study, a novel methodology to optimize the size of an autonomous hybrid photovoltaic-wind power system with battery storage is presented. A multi-objective optimization problem is considered with two objective functions, the total net present cost and a new reliability indicator called maximum expected energy not supplied, which is calculated using a probabilistic approach. The non-dominated sorting genetic algorithm-II was utilized to find the model solution. The results obtained with the presented methodology were compared with those from traditional methodologies, with the proposed methodology generating a set of feasible solutions, with respect to the system economy and reliability, which maximizes the use of renewable sources and reduces the size of the system backup.

1. Introduction

A number of factors have led to an increase in the consumption of electricity, including the world population growth, global economic development and industrialization. This results in an increase in the use of the main fossil fuels (oil, gas and coal), which increases the emission of greenhouse gases into the atmosphere, and therefore the environmental problems experienced on the planet.

BP Energy Outlook 2030 [1] reports that the world energy demand is projected to grow 1.3% year on average from 2016 to 2040. It is estimated that the highest growth will be for renewable resources, with a 7.0% year average. Despite this tendency, the dependence on fossil resources still remains high. These fossil resources accounted for 85.5% of total energy production in 2016.

Renewable energy sources have therefore become a critical aspect for the energy industry as they are part of the solution to environmental problems and the development of a sustainable future. They offer a clean way of generating energy, decreasing dependence on fossil resources, and allowing the electrification of remote places. Use of solar and wind energy has been increasing in recent years due to continuous technology improvements and cost reductions. Wind is the renewable source with the highest installed capacity, followed by solar photovoltaic. The cumulative installed capacity of wind systems increased by 11% in 2016 and the photovoltaic 24.8% [2].

While the use of solar and wind as energy sources has grown in the last decade [3], it is not possible deploy electricity from these sources for 24 h due to their stochastic and intermittent nature. In order to overcome this disadvantage, hybrid photovoltaic-wind energy systems have been designed. These systems include at least one renewable source and may contain conventional energy sources and storage systems. Fig. 1 illustrates a general scheme of these systems [4].

Designing a hybrid renewable energy system is a very complex process due to factors such as the stochastic behavior in some renewable sources, the non-linear characteristics of the system components and their integration, the imbalance between energy demand and load generation, and the high implementation and maintenance costs. Researchers have developed methodologies to find the optimum design of such systems, taking into account economic, reliability and environmental criteria [5].

The initial uses of these systems were focused on several areas. In telecommunications, a hybrid photovoltaic-wind system was designed to supply energy to a remote Base Transceiver Stations for mobile

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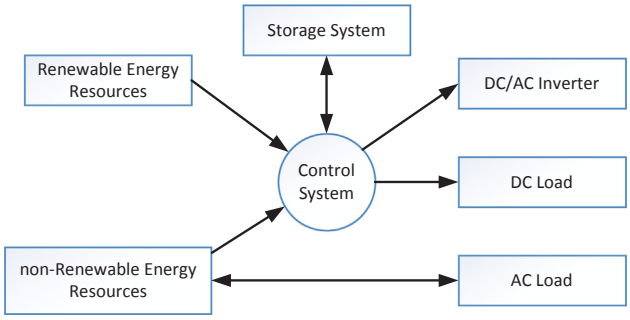

Fig. 1. General renewable energy system. Adapted from Ref. [4].

telephony companies [6]. Three places with high solar and wind potential were considered for the study. It was found that the proposed system is more economical and environmentally friendly than using diesel generator. In commercial and industrial applications, a feasibility study to implement hybrid PV-wind systems was carried out in a Jordan city [7]. Heating and cooling processes were analyzed taking into account the weather conditions and combining types of load. An economic analysis was conducted based on electrical tariffs for each category of application. In distributed generation systems, the design of a hybrid photovoltaic-wind system was presented as a microgrid, which is incorporated into a distribution system [8]. The design was based on an economic evaluation and cost optimization in a pool/bilateral electricity market.

Currently, these systems are being used in other applications. The design of a water pumping system based on a photovoltaic-wind hybrid system is presented in [9]. The researchers compared this system with one using only wind turbines or photovoltaic panels and decided which system is most efficient for a specific location. Hybrid photovoltaic-wind systems can also be incorporated in vehicles as mobile platforms for different uses. A design of these systems is presented by Yazici et al. [10]. In this design, the photovoltaic and wind energy were used to supply load and charge batteries and the energy excess was used for hydrogen production, which could be used for other applications. The design of a hybrid photovoltaic-wind system coupled to a reverse osmosis desalination unit is presented in [11]. The objective of this compound system was to obtain potable water using the energy of the hybrid system.

The high potential of sun and wind in many cities of the world, in addition to the changes in regulatory laws of the electricity sector, have enabled these technologies to combine to generate electricity, reducing the use of the conventional sources and thus decreasing the emissions of greenhouse gases to the atmosphere. Hence feasibility studies of these solar and wind resources systems have been performed for a number of locations. Yanxia and Wenjia [12] analyzed the economic impact of wind and solar photovoltaic penetration in the energy generation in China compared with the coal generation in 2016–2030 period. Zubi [13] carried out a techno-economic assessment to combine photovoltaic and wind energy with combined cycle gas turbines, open cycle gas turbines and a rigid base load to generate electricity in Spain. The results showed that a technology mix with 30% wind, 30% solar with conventional power cycles is feasible in this place.

Hence feasibility studies of these solar and wind resources systems have been performed for a number of locations. In a Saudi Arabia village, which was powered by a diesel power plant, Rehman et al. [14] carried out a feasibility study to reduce the diesel consumption. This was achieved with a penetration of 26% wind, 9% solar PV and maintaining the continuous power supply. In a Malaysian city, Ngan and Tan [15] performed the economic viability of seven scenarios by combining wind, solar photovoltaic, diesel and batteries. The authors analyzed the advantages and disadvantages of each scenario. In Ethiopia, Bekele and Palm [16] modeled a renewable energy system to supply energy to a community of 200 families, which lacks the electricity service. The authors concluded that the hybrid systems implementation in this country would have benefits in all aspects, because its total electricity coverage is less than 15%. A technical and economic analysis of these systems was carried out by Hiendro et al. [17] in an onshore remote place in Indonesia. The system feasibility was analyzed in terms of costs and it was found that the solar source delivers the highest energy production. Ahmad et al. [18] analyzed and concluded that it is possible to design wind-photovoltaic-biomass hybrid systems techno-economically viable and commercially applicable in a Pakistan province and developed a methodology that could be applied in other places with similar characteristics. Nandi and Ghosh [19] analyzed a stand-alone system in a Bangladesh community. Authors found that the optimal design may not be economically feasible, but they showed that environmental and cost benefits obtained are greater than if the grid were extended. Bayod-Rújula et al. [20] analyzed the best integration between a hybrid wind-photovoltaic system, batteries and the grid. The aim of this research was to supply energy to a typical residence in Aragon Spain taking into account its consumption. Yahiaoui et al. [21] evaluated a hybrid energy system operating in a not connected region in Algeria. The results predicted that 100% of the demand could be supplied from renewable sources and using diesel generation as backup system.

The aim of this paper is to present an optimization methodology to design a solar photovoltaic-wind hybrid system based on a multi-objective model. The model considers an indicator to evaluate the economic feasibility of the system and a new indicator to evaluate its reliability. The new reliability indicator includes the probabilistic behavior of the renewable energy sources and the output power, and maximizes the use of renewable energy so that the size of the storage system is minimized.

The analysis is performed in two phases. First, the potential of the proposed indicator with respect to the traditional indicators is investigated. For this, the system is optimized considering four models under a multi-objective approach, taking into account different reliability indicators and the economic feasibility of the system. For all models, the economic feasibility is analyzed using the net present cost. The analysis is carried out under different operational scenarios including: high and low demands, variable and constant demands, two speed schemes and two solar radiation schemes. Second, the solution to the optimization problem is compared with standard solution methodologies. For this, the optimization is carried out under a mono-objective model using the net present cost (*NPC*) as the objective function with the same parameters and conditions using HOMER (Hybrid Optimization Model for Electric Renewable) and HOGA (Hybrid Optimization by Genetic Algorithms software). These software are tools developed to design power systems using renewable and conventional sources.

This paper is organized in six sections. Sections 2 and 3 provide general information about optimization and modeling of a hybrid photovoltaic-wind system. Section 4 presents the optimization models considered. Section 5 details an application case and a comparison of the solutions, and finally, in Section 6 the conclusions are presented.

2. Hybrid solar photovoltaic-wind system optimization

In order to find the optimal design of a hybrid photovoltaic-wind system, the process is represented by a mathematical programming model with objective functions and constraints. The aim is to identify the optimal set of components (wind turbines, solar panels and batteries) subject to satisfying certain criteria, such as economic, reliability, environmental restrictions. The methodology consists of defining a mono-objective or multi-objective optimization problem, grid-connected or stand-alone, the indicators, solution methodologies and solution techniques. Fig. 2 illustrates the different schemes to formulate and solve a hybrid wind solar photovoltaic system optimization.