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A novel approach for optimal combinations of wind, PV, and energy storage system in diesel-free isolated communities

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HIGHLIGHTS

- A DC configuration is proposed for the renewable energy integration.
- PV-wind system should be considered simultaneously for the optimum configuration.
- Range of batteries can be determined by wind and solar potential.
- Wind turbine is an essential power component in renewable energy real installation.
- Optimum fraction of wind turbine in hybrid renewable energy systems.

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ABSTRACT

A new approach for optimal combinations of Hybrid Renewable Energy Systems (HRESs) is proposed, for diesel-free remote communities and related decision-making problems. The objective of the design is to satisfy the load with total cost's minimization considering related constraints, where all analytical equations are given. The proposed system is a DC configuration for renewable energy integration in which Wind Turbines (WTs) are connected to the DC bus and the battery system removes the fluctuations in the DC bus. The WT is assumed to be well controlled to obtain the power curve and provide proper electricity to the grid. It is found that WT and Photovoltaic (PV) systems should be considered simultaneously on diesel-free generation islands to achieve a reliable and optimized configuration. A novel strategy is introduced for determining the range of batteries, which can be determined using the renewable energy potential to satisfy the load. It is also demonstrated that WTs are an essential power component in real HRES installations. It is illustrated that the range of WT operation must be first taken into account in real installations. Increasing WT fraction from an initial value, for instance 8%, to a desired value of about 33%, can lead to significant reductions in total cost as well as in the number of PV systems and batteries, even if the WT cost is significantly higher than that of PVs. A WT fraction higher than approximately 50% should not be considered. Finally, discussions are extended to consider the optimum WT fraction in a HRES.

1. Introduction

In recent years, there has been a significant increase in the utilization of renewable energy sources. The optimum design of renewable hybrid systems has been the main objective of many investigations. From the South Korean energy policy perspective, South Korea's domestic energy consumption will form a very large proportion of the total energy consumption supplied by renewable energy, rising to approximately 11% by 2030.

Due to several practical issues such as environmental pollution caused by fossil fuels and fluctuation in fuel costs, renewable energy resources have become one of the most efficient solutions for environmental pollution prevention and sustainable energy development [1]. The total primary energy supply of South Korea was 275,688,000 in 2012, while the contribution of renewable energy to this was only 2.75% (7,582,846) [2]. South Korea has seen abundant and increasing sales of renewable energy technologies, from 1,461,000 million Korean Won (KRW) in 2004 to 8,128,000 million KRW in 2010. Over the last few years, there has been a rapid growth in the development of renewable energy technologies.

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Wind turbine (WT) and photovoltaic (PV) systems produce electrical power that involves zero greenhouse gas emissions and fossil fuel consumption. Robustness and simplicity of design, as well as low maintenance requirements, make PV and wind generation systems much easier to use and more cost effective than other renewable energy generation systems [3]. However, the power output of wind and PV systems is significantly affected by variability in wind speed and solar radiation. Hybrid wind and PV power systems accompanied by battery storage enhance system reliability and efficiency [4].

The fundamental drawback of renewable energies is the fluctuation in output power, especially in PV systems, and it is essential to mitigate these fluctuations. Battery storage in hybrid systems is a vital factor to take into consideration; battery systems contribute to compensating seasonal variations in renewable energy resources, most significantly in PV systems, as well as smoothing out load fluctuations. Battery systems stabilize PV systems to run at a stable and constant output, and provide ride-through loads to compensate for instantaneous drops in energy supply, for example when there is a lack of solar radiation. Several energy sources such as WTs, PV systems, diesel generators and fuel cells can be combined to make a hybrid renewable energy system (HRES) [5].

Economically, the optimal sizing of wind/PV/battery hybrid systems should be determined to minimize the total annual cost of the system [6]. In other words, the main motivation of the optimum design is to obtain the optimal number of WTs, PV panels, and batteries that minimize the total annual cost of the hybrid system with respect to some constraints. In recent years, the optimal design of hybrid wind/PV systems has been widely investigated. For instance, optimal sizing of a hybrid wind/PV system based on a simple graphical construction without considering the actual size of the battery was determined in [7]. Ref. [8] proposed a method to optimize a hybrid wind/PV system considering the unit cost of the produced electricity and the total system cost. The optimization was assumed to be based on a constant load. A novel method using a genetic algorithm is proposed in [9] to investigate the optimal sizing of stand-alone wind/PV systems. A general concept for finding the optimal design of hybrid wind/PV systems for either grid-connected or stand-alone applications is discussed in [10]. Ref. [11] developed an algorithm that uses power demand, insolation, and hourly average wind speed to determine the optimal size of wind/PV systems without loss of power supply probabilities. The authors in [12] proposed a set of match calculation methods for optimum sizing of PV/wind hybrid systems considering local hourly measured meteorological data, price of the components, reliability requirements of the power supply, and load demand. The authors in [13] used mixed integer linear programming for the optimum design of a rural hybrid wind-PV system based on either integer or binary variables. A linear mathematical model based on the graphical method was developed to minimize the total cost of a HRES in [14]. A stochastic mixed integer programming model using Benders' decomposition algorithm and Pareto-optimal cuts is proposed for optimal design of a HRES in [15]. System design, storage devices, WTs, thermal generators, and the transmission network were included in the model. The authors in [16] investigated an optimization framework to design HRESs considering hydrogen storage, PV panels, WTs, accumulators, an electrolyzer, a compressor, storage tanks, a diesel generator, and a fuel cell. A multi-objective evolutionary and genetic algorithm has been used to find the optimal configurations of hybrid systems with the goal of minimizing the total cost throughout the useful life of the installation, as well as the unmet load and pollutant emissions [17]. An optimization method using an adaptive neuro-fuzzy inference system is proposed for optimal design of a PV/wind/battery hybrid system with the purpose of reducing total annual cost and excess electricity [18]. A linear program was developed for the optimal configuration of 100% renewable energy systems in terms of the overall system costs in [19]. The authors in [20] described the techno-economic evaluation of a standalone hybrid solar-wind system with battery energy storage in terms of cost of energy and system net present cost. They also considered the effects of WTs, PV panels, and battery bank sizing on the system's economic performance. Optimal sizing of a stand-alone hybrid wind/PV/diesel/battery system aimed at minimizing the offered service is investigated in [21]. In that study, the authors discovered that the reliability of the system was enhanced when all the proposed components are used. Optimal dimensions of a hybrid diesel/wind stand-alone system on the basis of minimum long-term electricity production cost were studied in [22]. It was stated that the proposed hybrid stand-alone system was a significant techno-economic solution to meet the load demand of remote areas, especially in regions where the wind potential is either medium or low. Optimal sizing of a hybrid PV/wind/battery system was also conducted with the objective function of lowest cost of energy in [23]. The main goal was to demonstrate that 40% of the total energy production of a hybrid energy system can be achieved by wind generation if the wind potential is high. The applications of autonomy analysis and a response surface methodology in optimization problems of hybrid energy systems are studied in [24]. One optimum design technique using a genetic algorithm for a hybrid PV/wind system aimed at achieving the desired loss of power supply probability with the minimum annualized cost of the system is developed in [25]. A discrete-time Mixed Integer Linear Programming method for the simultaneous optimization of energy production and consumption tasks in hybrid energy systems to maximize the total profit is presented in [26]. Simulation, modeling, optimum sizing, and economic analysis of renewable energy systems have been widely investigated using the Hybrid Optimization Model for Electric Renewables (HOMER) software (e.g., [27–31]). For instance, the authors in [31] used the HOMER software to investigate the feasibility of utilizing renewable energy systems in a small hotel considering grid-connected and stand-alone configurations. They observed that the stand-alone configuration can economically satisfy the load in comparison with the grid-connected option. Refs. [32,33] surveyed computer tools and methodologies for optimum sizing of renewable energy systems and showed that the HOMER simulation software has several advantages over other available renewable energy simulation software. Literature reviews show that many studies based on various techniques have been conducted to analyze the feasibility and find the optimal design of HRESs on different islands. In the optimization techniques mentioned above, the optimization problem is normally based on linearly changing the values of variables or probability programming techniques. In addition, the aforementioned techniques do not take into consideration the real characteristics of the power components. The system proposed here is based on a DC configuration for renewable energy integration (i.e., WTs are connected to the DC bus), where the battery system removes the fluctuations in the DC bus. The WT is assumed to be well controlled to obtain the power curve and provide proper electricity to the grid. This concept is mainly overlooked in previous studies [21–35]. At present, to the best of the authors' knowledge, a comprehensive optimal combination of HRESs has not been addressed. Almost all configurations developed in previous studies are neither flexible nor practical in real installations. This paper opens up a new avenue of investigation toward developing a benchmark for renewable energy optimal combination for diesel-free remote islands. The objective function is considered as total cost minimization considering the related constraints, where all analytical equations are given. The WT and PV systems must be considered simultaneously in diesel-free hybrid renewable energy systems to achieve a reliable and optimized configuration. The