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Dynamic multi-stage dispatch of isolated wind–diesel power systems

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ABSTRACT

An optimal dispatch strategy is crucial for an isolated wind–diesel power system to save diesel fuel and maintain the system stability. The uncertainty associated with the stochastic character of the wind is, though, a challenging problem for this optimization. In this paper, a dynamic multi-stage decision-making model is proposed to determine the diesel power output that minimizes the cost of running and maintaining the wind–diesel power system. Optimized operational decisions for each time period are generated dynamically considering the path-dependent nature of the optimal dispatch policy, given the plausible future realizations of the wind power production. A numerical case study is analyzed and it is demonstrated that the proposed stochastic dynamic optimization model significantly outperforms the traditional deterministic dispatch strategies.

1. Introduction

Isolated hybrid wind–diesel power systems have a great potential application for remote communities and facilities, such as islands and rural areas. The power grids in those areas are normally disconnected or with very limited connection to the mainland energy system, because the cost to extend or upgrade the connection between the main power grids to the local communities is extremely high.

The benefits of integrating wind energy sources in remote isolated power systems are not just limited to savings in fuel consumption. Indeed, compared to the traditional diesel system, integrated wind power could offer additional advantages such as providing extra energy capacity to the micro-grid, reducing pollution and greenhouse-gas emissions, and hedging the risk of unexpected fuel price increases.

A crucial issue when operating a hybrid wind–diesel system is the scheduling and operation of both dispatchable and non-dispatchable energy sources [1]. When operating the hybrid wind–diesel system, the decreasing of diesel efficiency due to the wind power uncertainty has been reported [2]. A smart dispatch strategy can increase the project cash flow by improving the efficiency of the diesel power genset while maintaining the security and reliability of the isolated system. Various factors must be considered when determining the optimal dispatch strategy, mainly the wind power uncertainty and the energy storage system [3].

Due to the intermittent nature of wind energy, stochastic models are needed to characterize the power output of wind farms [4]. Over the last decade, as a result of the rapid development of the wind power industry, wind energy forecasting and modeling techniques have been researched extensively, and several methods can now be found in the technical literature (see, e.g., [5,6], and references therein). Thanks to those advanced wind power models, power system managers can perform operational actions using more meaningful and precise information.

For its part, the use of energy storage devices facilitates the shifting of the energy load and energy production [7]. For instance, in some isolated power grids the installed renewable power capacity may be higher than the average power consumption. Then, according to Kusakana [8], the excess of renewable power production can be stored and used in periods of high power net load. Nowadays, different technologies, including but not limited to electrochemical batteries [9], hydrogen storage [10], flywheel systems [11], and pumped hydraulic energy storage [8], can provide short-term energy supply from a few seconds to a few hours, with a power output ranging from a few kW up to about one GW, and a total amount of energy stored varying from less than 1 kW h to tens of GW h [12].

The optimal power dispatch of a hybrid wind–diesel power system is path-dependent. This is so because the current state of the

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storage unit depends on the previous operational actions. As a result, a multi-stage decision process is needed to solve this problem.

In this paper, a dynamic multi-stage decision-making model is proposed to operate isolated hybrid wind–diesel power systems at minimum fuel consumption. A Markov decision process solved by dynamic programming is applied to determine the system states considering the future uncertainty. The model makes use of a probabilistic characterization of the future uncertain parameters to simulate the potential operation of the wind–diesel system under different conditions. The total fuel cost is minimized at the current time point plus the expectation of the fuel consumption in the subsequent periods.

A numerical case study is presented for discussion. The result shows that wind power uncertainty has a strong impact on the operating efficiency of the isolated wind–diesel power system. Compared to the deterministic dispatch strategies currently available in the technical literature, the dispatch policy resulting from the proposed optimization model exhibits a remarkable performance in minimizing the total fuel consumption of the wind–diesel system.

The remaining of this work is organized as follows: Section 2 provides a literature review in the topic and lists the main contributions of this work. Section 3 presents the model formulation and solution process. Section 4 implements the proposed method and compares it to existing ones using a practical case study. Section 5 discusses some practical issues when applying the proposed method. Section 6 sets out the main conclusions of this work.

2. Literature review and contributions

Today a number of commercial projects for hybrid wind–diesel power systems have been developed to provide power supply to isolated communities in different countries [13] (e.g. in Alaska, U.S. [14], in San Cristóbal Island, Ecuador [15], and in Aegean Sea islands [16]). Advanced control techniques have been designed to operate these systems and maintain the voltage, frequency [17], active power and reactive power [18] within the required limits [19].

The dispatch strategy is key to control the energy flow within the hybrid system in a cost-effective manner. Traditionally, the power dispatch of hybrid wind–diesel systems is mainly carried out using deterministic tools. In most of the applications and commercial softwares, including HOMER [20] and many other works [21], the dispatch strategy is based on the research conducted by Barley and Winn [22]. They propose several control strategies for the dispatch of the diesel generators in a hybrid system. In the "Load Following strategy", the power from the diesel generator is never used to charge the batteries. In the "SOC (State Of Charge) set-point strategy", the diesel generator is always running at full capacity, with the aim of charging the batteries until a pre-decided SOC is reached. Finally, in the "Full power strategy", the diesel generator runs at full capacity for a prescribed minimum period of time. They argued that by optimally choosing between the "Load Following strategy" and "Full power strategy", the resulting operational strategy can be virtually as effective as the ideal one.

These dispatch strategies have been widely accepted and applied in feasibility studies [23], cost analysis [24], and project design/planning [25] of hybrid wind–diesel systems. Simulation tools have also been developed based on these operational strategies [1]. According to Bernal-Agustín and Dufo-López [1], the most used examples include, but are not limited to, HOMER (Hybrid Optimization Model for Electric Renewables), developed by NREL (National Renewable Energy Laboratory, USA); Hybrid2, developed by the Renewable Energy Research Laboratory of the University of Massachusetts; and iHOGA (improved Hybrid Optimization by Genetic Algorithms), developed by the Electric Engineering Department of the University of Zaragoza, Spain. Some of these softwares can be freely downloaded from their websites.

Dufo-López et al. [10] present an improved model to control stand-alone hybrid renewable electrical systems based on genetic algorithms, by including new types of electrical load, and different methods for estimating the lifetime of batteries and storage operation. Gracia and Weisser [26] compare the fixed dispatch rule and a linear programming method on a one-year time series of wind speed data in hourly resolution, and they prove that the linear programming solution outperforms the fixed dispatch rule.

The dispatch strategies mentioned above have not considered the uncertainty in the wind source. Optimization methods such as stochastic programming and stochastic dynamic programming are generally applied in the energy sector to solve the power scheduling problem including uncertainty. Garcés and Conejo [27] use stochastic programming to solve the self-scheduling problem for a power producer to maximize the profit considering uncertain price. Uncertainty is usually modeled using scenario trees in stochastic programming [28]; however, this approach becomes quickly computationally intractable when dispatch decisions are to be made dynamically in multiple stages. Lujano-Rojas et al. [29] optimize the day-ahead load management strategy for residential consumers under a real time pricing demand response program, considering the ensemble forecasting of wind power, electricity prices, etc.; however, a decision scheme for shorter time horizons, for instance hourly-ahead, is still desired. To overcome these issues, a stochastic dynamic programming approach is applied instead.

Uncertainty modeling and forecasting are fundamental for operational researchers and engineers to design adaptive decision schemes. In the area of wind energy, a Weibull distribution is often used to characterize the probability distribution of wind speed from historical data [30]. Point forecasting of wind speed can also be carried out through a wide variety of methods [31]. In the last few years, both theoretical and practical research in the field of wind power forecasts has focused on various forms of probabilistic forecasting [6], which provide information on the development of the forecast uncertainty through the forecast series [4]. Numerical methods, such as artificial neural network [32] and extreme learning machine [5], can be applied to perform a probabilistic forecasting.

When operating a hybrid wind–diesel system, the development of the uncertainty is essential to model the plausible evolution of the system in the subsequent time periods over the scheduling horizon. Advanced optimization methods are therefore necessary to make the best use of the novel probabilistic forecasting techniques [6], where stochastic dynamic programming has a great potential.

Hu and Solana [33] apply dynamic programming to assess the value of a hybrid wind–diesel power plant using real option theory [34], to numerically solve the option problem, conditional values [35] should be correctly addressed. Madaeni et al. [36] implement a dynamic programming approach to estimate the capacity value of energy storage, and capture the effect of system shortage events in subsequent periods. Iversen et al. [37] introduce stochastic dynamic programming model to optimally charge an electric vehicle under the uncertainty inherent to its use.

A dynamic programming method is proposed in this paper to optimally determine the diesel power output for a hybrid wind–diesel power system. Compared to the aforementioned methods, this paper contributes to the literature by accounting for the impact of power consumption and renewable production