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Operational optimization and demand response of hybrid renewable energy systems

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HIGHLIGHTS

- Hybrid renewable energy systems are reviewed and modeled.
- Energy management strategies for both generation and demand are developed.
- Receding horizon optimization is applied to increase reliability.
- Real-time prediction, optimization and demand-responsive are integrated.
- An application to a residential home is demonstrated.

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ABSTRACT

This paper presents a methodology to systematically formulate a hybrid renewable energy system (HRES), which consists of solar, wind and diesel generator as a backup resource as well as battery storage, from the preliminary design stage to the optimal operation. Detailed modeling of each system component is introduced as the basis for the simulation study. System sizing considering energy flows is conducted to obtain the optimal combination of photovoltaic (PV) panels and wind turbines. Energy management strategies from both the demand-side and generation-side are developed to realize the objectives of meeting the electricity demand while minimizing the overall operating and environmental costs. Day-ahead and real-time weather forecasting, demand response and model updating are also integrated into the proposed methodology using a receding horizon optimization strategy. The method is demonstrated through an application to a single-family residential home.

1. Introduction

Alternative energy technologies are receiving significant attention due to diminishing traditional fossil fuel resources and increasing worldwide energy demand. The use of renewable energy resources offers notable environmental benefits by reducing dependence on fossil fuel resources and carbon emissions to the atmosphere [1]. Many countries and local governments have mandates for electricity utilities to significantly increase the portion of power generated from renewable resources as part of their energy portfolio. For example, in California, Governor Brown signed a bill in 2011 requiring that "…[a]ll retail sellers of electricity shall serve 33 percent of their load with renewable energy by 2020." [2].

Hybrid renewable energy systems (HRES), which consist of solar, wind and other energy generation and storage units, have been widely studied in recent years owing to their strength in dealing with the intermittent generation and scarce supply of a single renewable resource. Many studies have been reported on the modeling, control and optimization of hybrid energy systems from design to operation [3–6]. [7] comprehensively reviewed HRES for power generation in stand-alone applications and claimed that the high manufacturing and maintenance costs of wind turbines and photovoltaic (PV) panels are a major concern for renewable energy penetration into the grid. [8] applied model predictive control to solve the economic/environmental dispatch problem for a regional electric power system with many intermittent resources. [3] demonstrated several simulation tools to size and operate an integrated solar generation system involving PV generators, compressed-air energy storage and super-capacitors. As there are several different stages in the life cycle of HRES [9], it is necessary to consider the system design and operation from a variety of time scales. Whether a whole life analysis or a daily schedule is considered, real-time optimization presents a significant opportunity to manage HRES systematically.

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Operational research concepts have been widely applied to allocate generation capacities among all resources in a hybrid energy system [10–12]. Based on certain pre-defined priorities/conditions, such as always operating renewable generation at maximal capacity, the optimal power or energy dispatch strategies can be obtained. However, while most previous operational research or applications of renewable energy systems take it for granted that renewable resources should always be operated at maximum capacity considering their low cost and environmental impact, such a strategy may cause the overall system to face over-production problems in the future, and can lead to less economical solutions. It is becoming increasingly valuable to obtain the dispatch strategies by optimizing the system performance without pre-determined priorities so that the output from renewable generation can also be curtailed, which will be one of the contributions of the present paper. With a similar interest, but a different focus on the control system design, Qi et al. [13–15] demonstrated how automatic control techniques can be applied to the management and supervision of hybrid renewable energy generation systems in both stand-alone and grid-connected modes. The utilization of supervisory control can achieve a dynamic optimal balance among the renewable generation subsystems, the smart grid and the demand. Moreover, the scale of load matters for the management of renewable energy generation. Compared with the management of renewable energy generation applied to a large region or even the whole country [16–18], small-scale applications such as those for residential usage in a stand-alone mode can be far less complicated but also bear even more potential uncertainties related to electricity generation and demand, and the feasibility and efficiency of these off-grid HRES to meet load demand of single family communities need further study [19,20]. Focusing on small-scale utilization also allows us to analyze user behavior such as load shifts which is another important aspect of power system operation known as Demand-Side Management (DSM), consisting of Energy Efficiency (EE) and Demand Response (DR) [21]. DR refers to the change in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices, or when system reliability is jeopardized.

Currently, HRES are mainly applied in off-network communities and remote areas where the grid connection is unavailable and construction is expensive [22]. However, with the increased emphasis on sustainable development, it seems plausible that in the future these clean generation technologies would be more widely applied to common residential buildings, even though grid electricity is available. In this context, demand response plays a significant role in balancing the less stable generation from renewables. Demand response strategies are generally categorized as benefits-driven or penalties-driven, while both are based on price incentives. Residential Time-of-Use (TOU) electricity pricing, for example, encourages users to shift their consumption to other time periods of a day in response to the varying electricity price [23]. [24] considered load shifting and demand reduction in buildings through model predictive control and economic optimization. However, the lack of effective building automation systems and the resulting insufficient knowledge for users about how to respond to TOU prices are two major barriers for fully utilizing the potential benefits of real-time pricing tariffs and realizing DR [25].

This paper focuses on the optimal design and operation of a residential HRES, comprising photovoltaic panels, wind turbines, backup fossil fuel generation, such as diesel generators, and storage units such as batteries, to support a single family house load. The system is operated in a stand-alone mode with the assumption that the electricity consumers are the same as the producers, and therefore the dispatch of load in response to generation availability and cost is achievable. This novel combination of demand response and renewable energy generation is the key contribution of the paper. The stand-alone renewable energy generation system is first described in Section 2, which includes a detailed modeling description of each system component in Section 2.1 and two approaches for system sizing in Section 2.2. The receding horizon optimization is then introduced in Section 3 to demonstrate how the optimal dispatch among all available resources is realized by considering the real-time performance of the generation system to guarantee that the consumer electricity demand is satisfied and that the overall system economic and environmental costs are minimized. Demand-side management is then discussed from a day-ahead planning stage and a real-time demand response viewpoints in Section 4, and advantages of the proposed approach are analyzed. Finally, conclusions and possible directions for future research are discussed in Section 5.

2. Stand-alone renewable energy generation system

2.1. Modeling of energy conversion systems

Renewable resources bear intermittency and inherent uncertainty due to their discrete generation and dependence on weather conditions. To increase the stability and reliability of the generation system, some other electricity resources are also considered to form a hybrid system. One option is to use backup generation using diesel or other fossil fuels as energy resource, and another option is to include storage units, the most commonly used among which are batteries, such as deep-cycle lead-acid batteries. A schematic of the HRES considered in this work is depicted in Fig. 1. The characteristics of each system component are discussed next.

2.1.1. Solar energy conversion system

Solar energy is converted to electricity through a system which contains PV modules to convert sunlight into electricity, and an inverter to convert the direct current (DC) from the modules into an lternating current (AC). PV performance models are used to obtain the current–voltage (I–V) curve and the Maximum Power Point (MPP), which can help optimize the performance of the PV system. A large number of PV performance models have been developed in the literature, among which the five-parameter array performance model has been widely used in both research and commercial applications [26–28]. The steady-state performance of a PV module is described by the relationship:

$$I_L - I_S\{\exp[\alpha(v_{pv} + R_S i_{pv})] - 1\} - \frac{v_{pv} + R_S i_{pv}}{R_{Sh}} - i_{pv} = 0$$
$$P_{pv} = v_{pv} i_{pv} \tag{1}$$

where P_{pv} is the constant power drawn, v_{pv} and i_{pv} are the operating voltage and current of PV modules respectively. I_L is the light current, I_S is the diode saturation current, R_S is the series resistance and R_{Sh} is the shunt resistance. The ideality factor $\alpha = q/n_s kT$, in which $k = 1.380710 \times 10^{23}$ J/K is Boltzmann's constant, $q = 1.6022 \times 10^{19}$ is the electronic charge, $T = 298$ K is the temperature, and n_s is the number of cells in series. The I–V curves based on this model at different times of a typical day are shown in Fig. 2. The maximum power points are also labeled in the figure. As can be seen, since the I–V curve is dependent on the solar irradiation, it will be different during the day, and the optimum power point shifts as well. The PV systems can be kept under optimal operation through maximum power point tracking [27].