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Impact of behavior-driven demand response on supply adequacy in smart distribution systems

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HIGHLIGHTS

- Impacts of demand response (DR) on smart distribution system reliability are assessed.
- Proposed a new DR model considering the variation of demand-side participation.
- Effects of communication systems on DR realization are considered in our evaluation.
- A hybrid algorithm combining operation optimization and reliability analysis is used.
- We verify the effectiveness of the proposed method on real distribution systems.

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ABSTRACT

As an integral feature of a future smart grid, demand response (DR) provides utility companies an emerging alternative to boost the reliability performance (e.g., supply adequacy) of power systems. Unlike for physical devices, the availability of DR is not only dependent on the operations of electric appliances on the demand side but can be affected by customers' behaviors. Thus, how or to what extent DR actions can affect power system reliability becomes an important issue for utilities. In this paper, a new approach for assessing the contribution of incentive-based DR to the supply adequacy of smart distribution systems (SDS) is presented. Compared with existing methods, our method explicitly captures the varying availability of customer DR capabilities. We introduce a behavior-reinforcement procedure to model the correlation of users' participation willingness with their historical DR profitability. Then, a strategic DR dispatch strategy can be developed to optimize users' DR availability bids in the market. In addition, the interdependency between a communication system and DR operation has also been considered. A hybrid algorithm based on sequential Monte-Carlo simulation and an optimal load dispatch method is employed to evaluate the system reliability in this context. The proposed approach is illustrated using both a small-scale test case and a real regional distribution grid in China. The results demonstrate the effectiveness of the presented method.

1. Introduction

Enhancing renewable energy utilization is an important motivation for the development of smart distribution system (SDS) [1]. To achieve this goal, the deployment of renewable-based distributed generation (RDG) is necessary [2]. However, as different to conventional units, the power output of RDG are normally incontrollable due to the intermittency nature of primary sources (e.g. wind) and hence their massive insertions may bring about challenges for power balancing and may have a significant impact on the reliability of power supply [3].

To cope with the uneven operation due to RDG, one possible way for utilities is to use energy storage or fast-response generators (e.g. gas turbine) [4,5] to boost the resilience of supply. Nevertheless, in practice, these schemes will not only incur extra expenses in economics, the potential generation emissions that involved may also offset the intrinsic benefits of RESs.

Because of these limitations, demand response (DR), as an emerging smart-grid technology, is attracting growing popularity in recent years [6]. Unlike the supply-based solutions, DR programs are primarily dedicated to exploiting the flexibility from demand

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side. Under the context of SDS, the presence of advanced metering infrastructures (AMI) facilitates bi-directional information exchange between users and the grid, making it feasible to monitor and control the way of end-use consumptions in real time [1]. In this light, from the system operator point of view, DR in the form of load reduction (deferral) during times of emergencies can be viewed as virtual operating reserves, which provide extra capacity (supports) to the system and contribute to the supply adequacy [7,8]. Therefore, for the economics of long-term planning, it would be critical to quantify and fundamentally indicate to what extent the DR resources could be relied on to guarantee reliability target.

In recent years, extensive research efforts have been dedicated to estimating the effect of DR on the reliability performance of power systems. For example, in [9], Zhou et al. propose an evaluation framework for investigating the contribution of DR to supply adequacy. They demonstrate that DR can reduce the occurrence of outages and that the level of improvement is influenced by the restoration properties of the loads. The applicability of smart appliances and electric vehicles for the auxiliary service market is analyzed in [10,11] using Monte-Carlo simulations. In practice, the unpredictability of human behavior may cause failures in DR operation. Therefore, a multi-state DR model is formulated in [12] to investigate the impact of this unpredictability on system reliability. Similarly, the contribution of DR programs to the short-term reliability of wind-integrated power systems is examined in [13]. In this study, a new optimal power flow approach that incorporates the lead time and the uncertainties associated with DR is presented. The authors of [14] assess the reliability benefits of DR in distribution systems. Similar studies are reported in [15] but with extensions for different financial mechanisms. Because the research in [9–15] is confined to a single type of electricity users, an investigation of DR effects that considers the diversity of load sectors is performed in [16].

In the above studies, DR activities are generally implemented via system-led, incentive-based and direct-control programs. Most of these studies hypothesize that the availability of DR potential is only dependent on the intrinsic conditions of consumers (e.g., load composition and compliances) and is independent of the motivation mechanism applied by the utility.

In reality, however, DR actions imply that users have to change their original consumption habits. Therefore, whether customers accept these changes and to what extent they are affected by these adjustments become critical factors [17,18].

In the electricity market, the primary incentive for consumers to enroll in DR is to obtain economic benefits. Individuals may opt out of a DR program if the discomfort they experience is greater than the economic rewards they can acquire. In practice, because DR deployment is implemented by the grid operator, inappropriate scheduling tactics would decrease customer participation willingness. For this reason, estimating the reliability contribution of DR without fully considering the impacts of the human factor may cause significant errors with respect to the truth of the case. However, little attention has been given to this problem so far.

To fill this gap, this paper presents a new methodology for analyzing the reliability enhancement feature of DR in the context of a smart distribution system (SDS) with a high share of RDG. Distinct from existing studies, the human-related aspect that is associated with DR activities is especially considered in this study. We develop a composite model to characterize the DR availability during operation. It can describe how the willingness of customers to participate in DR is affected by the profitability they reap from the program. The resulting outputs are synthesized with the load characteristics and the operational state of communication systems (i.e., advanced metering infrastructure, AMI) to determine the estimated DR capacity of the users in each time period. The proposed model is integrated in the reliability evaluation of SDSs, and sequential Monte-Carlo simulation (SMCS) and optimal load dispatch method are jointly employed to estimate the DR effect.

The rest of this paper is organized as follows: The reliability modeling of SDS components is described in Section 2. This is come after by Section 3, where a new model that considers human factors is developed for DR characterization. Subsequently, procedures for evaluating the reliability benefits of DR are elaborated in Section 4. Section 5 and Section 6 provide the results of an illustrative example and a large case study, respectively. Finally, some relevant conclusions are drawn in Section 7.

2. Reliability modeling of the components in SDS

The configuration of a typical SDS with DR is illustrated in Fig. 1. The system is composed of generating units, transmission lines and AMI; all components are managed by the utility company in a centralized manner.

In this system, both renewable energy generators and conventional power sources exist via either controllable distributed generation (CDG), e.g., gas turbines, or transformers in a distribution substation. In addition, all households are assumed to be equipped with a smart meter (SM), which enables users to respond to DR requests by automatically adjusting their load consumptions.

In this study, as we primarily focus on the contribution of DR to SDSs, our model assumes that transmission lines are 100% reliable and disregards possible contingencies in the network, in accordance with [15,16].

2.1. Generating units

The reliability model of generating units in SDSs consist of two aspects: mechanical availability and fuel supply [19]. In practice, the mechanical part can typically be demonstrated using a two-state Markov model [20], which represents the normal state and the failure state of the unit. In contrast, the fuel supply model may have different forms depending on the intrinsic nature of the technology [19].

In this study, we assume that CDG provide deterministic power outputs, that is, if no mechanical failures occur, CDG units can operate at any requested level in their nominal capacity limits without any uncertainty. For simplicity, only wind power generation is considered to be renewable-based DG (RDG) and is incorporated in this work. The variations in wind speed are represented by an autoregressive moving average (ARMA) time-series model [21], and real historical wind speed data are employed to develop the model. Given wind regimes, the available power output from a wind turbine (WT) can be derived based on their operational characteristics [20].

Transformers are stationary devices that serve as the major power source for SDSs. Although transformers can be controllable, the occasional fluctuation of the grid supply may cause uncertainties in their operation. To account for this effect, the power injection from the external grid is assumed to follow a uniform distribution of $[0.8,1]$ with respect to the substation capacity, as suggested in [20].

2.2. AMI

In SDSs, AMI serve a key role in the fulfillment of DR tasks. AMI provides a bidirectional communication path by which the field measures of demand data can be gathered and subsequently processed by the utility operator in real time. Thus, the load control signals can be delivered to the end users and automatically enacted [22]. Due to the strong interdependent nature of AMI, its availability significantly impacts the reliability benefits of DR.