Impact of behavior-driven demand response on supply adequacy in smart 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 uncontrollable 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...
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, 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.
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