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Grid-side flexibility of power systems in integrating large-scale renewable generations: A critical review on concepts, formulations and solution approaches

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ABSTRACT

Though considerable effort has been devoted to exploiting generation-side and demand-side operational flexibility in order to cope with uncertain renewable generations, grid-side operational flexibility has not been fully investigated. In this review, we define grid-side flexibility as the ability of a power network to deploy its flexibility resources to cope with the changes of power system state, particularly due to variation of renewable generation. Starting with a survey on the metrics of operational flexibility, we explain the definition from both physical and mathematical point of views. Then conceptual examples are presented to demonstrate the impacts of grid-side flexibility graphically, providing a geometric interpretation for a better understanding of the concepts. Afterwards the formulations and solution approaches in terms of grid-side flexibility in power system operation and planning are reviewed, based on which future research directions and challenges are outlined.

1. Introduction

With the rapid growing penetration of renewable generation, significant challenges of security and economics have arisen in power system operation due to the intermittent and stochastic nature and low predicability of renewable generation. Thus sufficient power system flexibility is required to cope with the new issues which have not been experienced before. This paper is focused on the operational flexibility on the grid side of power systems with regard to operation and planning. For short, we call it "grid-side flexibility". The aim of this paper is to provide a comprehensive understanding on its concepts, formulations and solution approaches. Based on the review, the future research directions and challenges in optimally utilizing grid-side flexibility to facilitate a secure operation of the power system with high-penetration renewable generation can be figured out.

Power system flexibility is not a new concept, as power systems have always had to utilize generation resources, control systems and business practices to ensure that system supply-demand balance can be retained within the industry standards [1]. Conventional methods to accommodate load uncertainty include regulating reserve, automatic generation control (AGC) and so on. However, these methods may not be able to provide sufficient flexibility to address the inherent uncertainty and volatility of renewable energy generation, which cannot be forecasted as accurately as electricity demand nowadays. To cope with the great challenge, new technologies have been proposed and constantly developed.

The flexibility of power system can be generally divided into three categories: generation side, grid side, and demand side. In the generation side, different kinds of approaches have been applied in unit commitment and economic dispatch to enhance generation-side flexibility. Stochastic optimization has been studied extensively, which explicitly incorporates uncertainty in the decision process [2–4]. Most of the models rely on pre-sampling discrete scenarios and aim to minimize the expected cost. Instead of scenarios, interval optimization uses confidence intervals to characterize uncertainty, and derives optimistic and pessimistic solutions for satisfying system operational requirements [5,6]. Taking advantage of uncertainty set, a probabilistic distribution is not required in robust optimization [7–9]. An optimal solution is obtained, which immunizes against all the uncertain data contained within the given uncertainty set. Other approaches, such as fuzzy mixed integer program [10] and minimax regret program [11], have also been applied to help accommodate large-scale volatile renewable generation.

In the demand side, demand response management is acknowledged

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to improve the operational flexibility [12,13]. It has been applied in different aspects, such as unit commitment [14,15], real-time dispatch [16], and regulation provision [17] to cope with uncertainties in power system operation. Different schemes have been suggested, such as price-based [18] and coupon-based mechanisms [19] to name a few, in order to create incentives and encourage participation of demand response.

Compared with the flexibility from generation and demand sides, the grid-side flexibility has drawn less attention to date. Physically, power network provides sufficient capacity for transferring power from generation plants to consumers, which is traditionally considered as a fixed structure. However, due to the integration of large-scale renewable generations, the operation of power network has been pushed much closer to its technical limits than before. As a consequence, new problems arise which can hardly be resolved when there is lack of grid-side flexibility. First, the actual outputs of uncertain renewable generation may remarkably deviate from the forecast, causing high operational risk or congestion. The congestion can further increase operating cost and limit the usage of available flexibility resource from the generation and/or demand sides. Second, renewable generation usually requires the support of sufficient reactive power, imposing additional risk of voltage instability on power system operation.

In this context, novel technologies have been developed to exploit the potential flexibility of power network, making it a crucial supplement to generation-side and demand-side flexibility, and also an effective approach to address issues associated with congestion and voltage stability. Line switching has changed the traditional idea of a power network with a fixed topology, enabling power flow control by switching lines. Flexible AC transmission systems (FACTS) and high-voltage direct current (HVDC) technologies, have introduced more controllability into transmission networks [20–23]. They are mainly utilized to underpin reactive power compensation, voltage control, and power flow control [24], for the sake of increasing transmission capacity and power system security. Due to the powerful controllable power electronic devices, much faster controllability can be provided in comparison to the generation-side and demand-side resources.

In the literature, some reviews have focused on power system flexibility. Reference [25] classifies the scientific approaches, that have been used in flexibility demand studies, into technical, economic, and market potential categories, based on the results from German and European energy systems. Reference [26] reviews both supply-side and demand-side approaches, technologies, and strategies to enable high levels of variable renewable energy. Reference [27] classifies and discusses the possible flexibility impacts, including super short-term, short-term, mid-term, and long-term. It has been pointed out that new transmission technologies can enhance grid-side flexibility [27]. To the best of our knowledge, there is still lack of comprehensive reviews on grid-side flexibility so far.

This paper intends to provide a comprehensive understanding on "grid-side flexibility" of power systems, including its concepts, formulations as well as solution approaches, particularly when large-scale volatile renewable generation is integrated. To this end, the concept of grid-side flexibility is introduced first. Then the physical meaning of grid-side flexibility is explained, with the mathematical formulation of grid-side flexibility region. Moreover, geometric interpretation is explained via straightforward visualization, providing an intuitive understanding on the effects of various resources of grid-side flexibility. It also reveals the potential benefits of grid-side flexibility in accommodating uncertainty in power systems. For making better use of grid-side flexibility, the state-of-the-art studies on the theory and application are reviewed, including problem formulations and solution approaches. Last but not least, future research directions and challenging problems are outlined. Fig. 1 summarizes the structure of the paper.

The rest of the paper is organized as follows. Section 2 introduces the concept of grid-side flexibility. Section 3 reviews the formulations related to grid-side flexibility in power system operation and planning. Section 4 reviews the associated solution approaches. Section 5 discusses the future research directions and challenging problems. Final remarks about the literature review and outlook of grid-side flexibility close the paper.

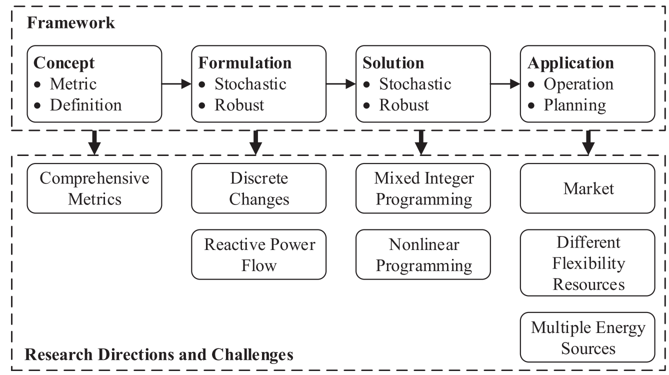

Fig. 1. Structure of the review.

2. Concepts of grid-side flexibility

In this section, first we review the metrics of power system flexibility. Then we explain our definition of grid-side flexibility in both physical and mathematical point of views. Moreover, geometric interpretation is explained via straightforward visualization, providing an intuitive understanding on the impacts of different grid-side flexibility resources.

2.1. Literature review of flexibility metrics

In the literature, a number of metrics have been proposed to quantify power system flexibility with regard to operation or planning. However, a comprehensive metric which explicitly quantifies grid-side flexibility with regard to renewable energy generation has not been proposed so far. As a supplement to generation-side and demand-side flexibility, grid-side flexibility is determined not only by the topology and parameters of power networks, but also associated with the constraints of generation-side and demand-side resources.

2.1.1. Power system operation

In power system operation, the metrics of flexibility mainly focus on generation-side flexibility, without consideration of grid-side flexibility. In other words, power networks are considered with fixed topologies and parameters.

Some metrics are based on the parameters of generators. In [28], a flexibility index borrowed from the process control literature is proposed to evaluate an operation strategy which provides balancing reserves to mitigate wind power generation uncertainty. In [29], a metric is presented to quantify the ability of a generator to cope with the flexibility requirement as below.

$$flex(i) = \frac{\frac{1}{2}[P_{\max}(i) - P_{\min}(i)] + \frac{1}{2}[Ramp(i)\Delta t]}{P_{\max}(i)} \tag{1}$$

where $P_{\max}(i)$ and $P_{\min}(i)$ are the maximum capacity and the minimum stable generation of conventional generator i, while $Ramp(i)$ is the average value of the ramping up and down rates of generator i per time period. Δt stands for one time period, say, one hour. This index is further extended in [30] for evaluating generation-side and demand-side flexibility while taking into account the impacts of transmission network. Inspired by the commonly used reliability metric, i.e., loss-of-load probability (LOLP), the lack-of-ramp probability (LORP) is proposed for real-time economic dispatch [31]. The system-wide LORP for the ramp-up case is defined in (2), which provides an assessment of the adequacy of the available system ramping capability from dispatched