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The values of market-based demand response on improving power system reliability under extreme circumstances

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HIGHLIGHTS

- Revealed the special contributions of DR on improving system reliability during 2014 North American Polar Vortex in PJM.
- Demonstrated unique merits in multiple aspects exhibited by DR verse conventional system-reliability-improving approaches.
- Discussed the challenges facing China on DR implementation during the transform from monopoly to open electricity market.

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ABSTRACT

Power system reliability faces serious challenges when supply shortage occurs because of unexpected generation or transmission line outages especially during extreme weather conditions. Alternative to conventional approaches that solicit aids from the generation side, operators can now leverage the demand-side resources through a variety of electricity market mechanisms to balance the active power and enhance system reliability. The benefits of the demand response (DR) have long been recognized in many works and empirical cases. Systematic analyses, however, have never been addressed to assess the values of the market-based DR for supporting system reliability. In this paper, a case study on the performance of DR in PJM Interconnections during the 2014 North American Polar Vortex is provided to highlight the significant contributions to improving system reliability and maintaining grid stability from DR programs. The unique merits in technical, economic and environmental aspects exhibited by DR during this extreme event verse conventional system-reliability-improving approaches are also demonstrated accordingly. Furthermore, we reveal the difference of DR programs driven by various existing market mechanisms after describing the fundamental DR functions. Values of various DR programs are also highlighted. At last, challenges and opportunities facing China on the design and implementation of DR programs during the transform from the monopoly scheme to an open electricity market during the power industry restructuring in recent years are also discussed.

1. Introduction

The reliability has long been the primary concern in all operational and planning activities of electric power systems [1]. Conventionally, system operators and planners solicit solutions mainly from the generation side to maintain a desired reliability level, which is typically characterized by the reserve margin in short-term operations and by the loss of load expectation in the long-term planning. This approach has proved to function effectively for decades. However, in recent years, reliability threats increase drastically due to the deepening penetration of various

Abbreviations: BRA, base residual auction; CP, capacity performance; CPP, critical peaking pricing; CSP, curtailment service provider; DAM, day-ahead market; DR, demand response; DSM, demand side management; DY, delivery year; EDC, electric distribution company; EE, energy efficiency; EUC, end-user customer; FERC, Federal Energy Regulatory Commission; IA, incremental auction; ISO, independent system operator; LMP, locational marginal price; LSE, Load-serving Entity; NERC, North American Electric Reliability Corporation; PJM, Pennsylvania-Jersey-Maryland; RPM, reliability pricing model; RTM, real-time market; RTO, Regional System Operator; RTP, real-time pricing; TOUP, time-of-use pricing; VER, Variable Energy Resource.

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energy resources (VERs). The uncertain and sometimes fast-changing VER outputs require more flexibility in power systems to respond to expected or unexpected changes in order to maintain reliability. Moreover, the frequent occurrences of extreme weather such as 2014 North America Polar Vortex [2] and recent heat waves in major cities in China also pose substantial threats to the system. Under such urgent conditions, the load may jump up in a short time yet the availability of conventional generators as well as the available transfer capability of the transmission network may deteriorate significantly, further resulting in deficiencies in reserves or even worse, shortages in power supply. Undoubtedly, the ability of a power system to ensure reliable operations, particularly during system emergencies, become increasingly critical.

There have been many works addressing power system reliability from the conventional supply and transmission sides. A long-term reliability-constrained tri-level robust power system expansion planning framework is proposed in [3] while considering multi-fold uncertainty from generation, transmission and demand sides. Reports [4,5] suggest the construction of new generation and transmission assets to maintain system reliability since New England region is increasingly reliant on the natural gas. Strategic operations of generations, storage devices and other conventional facilities are also addressed to improve the system reliability. However, with the increasing complexity of the power grid, power system planning with focuses on conventional facilities becomes extremely challenging from both technical and politic aspects, in particular for transmission line expansion [6]. Several major factors delay the developing pace of transmission network: lack of effective coordinated planning efforts to prioritize transmission projects to be built; lack of an efficient cost allocation mechanism to incentive transmission developers; and impediments to siting new transmission facilities from both state government and local residents.

The advent of massive demand-side resources brings new opportunities for system operators to leverage the flexibility and to maintain system reliability from the other side [7–12]. The concept of the demand response (DR), which evolved from a precedent concept called *demand side management* (DSM), has emerged as a new vehicle to help maintain power system reliability. Federal Energy Regulatory Commission (FERC) defines the *demand response* (DR) as “changes in electric usage by demand-side resources 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” [13]. The issuing of FERC Order 745 legitimized the eligibility of DR to be paid at same locational marginal price (LMP) in the wholesale markets [14].

Location-dependent impacts of demand responses are addressed in [15,16]. Meanwhile, paper [16] assess the benefits of residential DR programs in real-time energy market from the distribution level. Some preliminary works [17–19] discuss functionalities of the demand-side management from the perspective of electricity markets. Papers [20–22] propose several approaches or mechanism that encourages end users to sign up for the right contract and make use of the true value of their flexible demand activities. Reports [23–25] explore major industrial incentives for the development of DR under the smart grid paradigm and summarize the evolving/existing DR programs at different independent system operators (ISOs) or regional transmission operators (RTOs). In 2007, Southwest Power Pool established *Demand Response Task Force* and started to integrate DR programs into its market framework [26]. Florida Power & Light Company has sought out and implemented cost-effective DSM programs since 1978 and the efforts through 2015 have resulted in a cumulative summer peak reduction of 4845 MW and an estimated cumulative energy savings of 74,717 GW h at the generator [27]. Midcontinent ISO (MISO) market provides multiple opportunities [28] for DR participants: (1) demand response can offer into the energy market or spinning/supplemental reserve markets; (2) demand response can offer into the energy market and regulation/spinning/supple mental reserve markets and is treated identically to a generation resource; (3) Emergency demand response. MISO also describes in [29] the compensation for demand response in wholesale markets to comply with FERC Order 745. Both reliability-based and economic-based DR programs are adopted by New York ISO for different application purposes [30]. Recently, California ISO establishes a new policy to encourage the development of viable wholesale demand response products with direct market participation capability [31]. Upon completion, demand response services can be traded as market products by non-generation resources and used for maintaining power system reliability. In PJM, DR is a voluntary program that allows electricity customers to curtail their electricity usage during periods of high electricity prices [32]. In exchange, customers are compensated for decreasing their electricity use when requested by PJM.

Demand Side Management Methods released by National Development and Reform Commission of China formally initialized demand-side management efforts in China [33,34]. Last year, a new regulation policy entitled “Decree No. 9: Several Guiding Principles of Furthering the Reform of the Electricity Market” issued by China’s government urged the transform from monopoly structure to open electricity market under the background of great reform of the entire electricity sector [35]. Several provincial and municipal governments become demonstration sites for electricity reform, including Shenzhen, Guizhou Province, Hubei Province, Yunnan Province and so on. This big step towards market reform builds a solid background for China to develop DR [36,37]. In April 2015, following the No. 9 [2015] of State Council, National Development and Reform Commission released Notice on *Improving Demand Side Management Pilots through Emergency Power Mechanisms* to further strengthen the development of demand-side management and, thus, DR. Research work [38] discusses the potential role of DR in China as an efficient tool to alleviate energy shortfall. However, lack of appropriate incentive to implement DR programs by grid operators and lack of one competitive electricity market are both barriers for China to further develop DR programs [39,40]. We will briefly talk about opportunities and challenges to implement DR in China.

A comprehensive and deep understanding of the values that market-based DR can bring to power systems will surely benefit the development of future DR programs in China as well as the improvement of existing DR programs in US. To this end, we first present some statistics and facts from the 2014 North America Polar Vortex event to highlight the significant contribution that DR can make to maintain system reliability. With this special case in mind, we proceed to present a systematic analysis on the market-based DR programs using PJM as a representative example – from the fundamental physical functions to the various existing market programs, and from the retail market level to the wholesale market level – to reveal the values of the market-based DR in supporting system reliability. We note that the fundamental physical functions constitute the basis for the implementation of various retail DR programs, which further constitute the basis for the provision of DR products in the wholesale markets. In addition to relating the commodity properties of the DR to its physical properties, we also link the advantages of DR as a market product to its reliable and flexible physical nature.

The rest of this paper is organized as follows. In Section 2, we describe the 2014 North American Polar Vortex event and analyze the contribution of DR in PJM in maintaining system reliability during this event. Fundamental functions of DR, as well as its