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Benefits and challenges of electrical demand response: A critical review

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ABSTRACT

Advances in IT, control and forecasting capabilities have made demand response a viable, and potentially attractive, option to increase power system flexibility. This paper presents a critical review of the literature in the field of demand response, providing an overview of the benefits and challenges of demand response. These benefits include the ability to balance fluctuations in renewable generation and consequently facilitate higher penetrations of renewable resources on the power system, an increase in economic efficiency through the implementation of real-time pricing, and a reduction in generation capacity requirements. Nevertheless, demand response is not without its challenges. The key challenges for demand response centre around establishing reliable control strategies and market frameworks so that the demand response resource can be used optimally. One of the greatest challenges for demand response is the lack of experience, and the consequent need to employ extensive assumptions when modelling and evaluating this resource. This paper concludes with an examination of these assumptions, which range from assuming a fixed linear price–demand relationship for price responsive demand, to modelling the highly diverse, distributed and uncertain demand response resource as a single, centralised negative generator, adopting fixed characteristics and constraints.

Contents

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1. Introduction

Power systems are experiencing a period of rapid evolution. The previous status quo of large centralised generators operating within a monopoly is being replaced by a paradigm within which sustainability and competition are key priorities [1,2]. Vertically integrated power utilities have been dismantled and competitive market places [3,4] have been established to encourage the most effective use of generation and network resources. The push towards sustainability has resulted in the introduction of emission limits [5], carbon taxes, and most importantly going forward, ambitious renewable energy targets [6,7]. Under current operating practices, large amounts of expensive and carbon intensive system operating reserves are often required to ensure the security of power supply. This is a particular issue on power systems with high penetrations of uncertain renewable generation.

A number of solutions have been proposed to remedy this situation. Flexible generation resources are typically employed to maintain the system balance, while interconnection between power systems and regions can increase geographical diversity and smooth fluctuations in renewable power output. Electricity storage can also be used to balance periods of over- and under-supply of power. Demand response is a further option that is widely explored in the literature, but to date has had limited widespread usage. Demand response is regarded as an elegant solution to the issues of uncertain and fluctuating power supply, as the potentially significant latent flexibility of electrical demand can be harnessed to provide the required power system services to support renewable power generation. It is important to note that the benefits of demand response for renewable resources are neither the only, nor the primary, driver for demand response. Rather, the abilities of demand response are a fortunate coincidence with the recent focus on renewable generation.

A key advantage of demand response is the lack of major technological impediments, as much of the required communications and monitoring technology has been developed, with the roll out of advanced metering infrastructure already under-way in a number of regions [8,9]. The central remaining technological obstacle is the development of standards and protocols so that all components of this complex system are harmonised, and efficient communication can be achieved across the system. The greatest remaining challenge for demand response as a whole is to develop accurate control and market frameworks to ensure that this diverse and geographically distributed resource can be optimally employed, considering the needs of both the power system and the individual consumer. This is not an insignificant challenge, requiring the development of complex models of electrical demand at both the component and system levels. Simulation and forecasting models of demand are required to establish a realistic view of this resource for planning and evaluation purposes. These will facilitate the determination of its suitability for the provision of various system services and the value it can provide to the system. Going forward, operational models of demand will be required so that appropriate and accurate control signals can be issued. Such models are highly complex, as they must represent the highly diverse, dynamic and uncertain nature of demand, as well as the complexities of end-user interaction with the system.

1.1. Existing uses of demand response

Demand response is not a new phenomenon and has been employed in various forms across the globe for decades. The most obvious form of demand response is systematic load shedding, a last resort to avoid system blackout; however more sophisticated approaches have been implemented in a number of power systems.

Time of use (TOU) rates where consumers are subject to expensive tariffs during fixed peak hours, or cheaper rates during night hours, have traditionally been used to incentivise reduced peak consumption, and so-called “night-valley filling” behaviour respectively [10]. The objective of TOU rates is to reduce the difference between the peaks and troughs of the demand profile, thereby reducing the need for generator cycling or part-load operation. This allows a more efficient usage of generation, transmission and distribution resources.

Critical peak pricing (CPP) is an event-based tariff scheme employed for larger commercial and industrial consumers with the objective of decreasing peak loads. Under this scheme, higher electricity rates are applied during peak demand events. This approach has been adopted by the Californian independent system operator (ISO), and is most commonly employed to reduce loads during hot summer days from noon to 6 p.m. when the load from air conditioning units is excessive [11].

1.2. Future developments in demand response

Traditional approaches for demand response were adopted due to the predictable and cyclic nature of electricity demand and the dispatchable nature of generating resources. While this is appropriate in power systems dominated by conventional generation, systems with large penetrations of renewable resources require demand, and the system as a whole, to behave in a flexible manner on a continuous basis. This will allow the optimal usage of the renewable resource and ensure that the system balance is maintained. As such, continuous demand response is the focus of this paper. The concept of continuous demand response, and in particular the use of price signals to elicit this response, was proposed as far back as 1988 in the seminal work of Schweppe et al. [15] on spot pricing of electricity. In this work it was proposed that price signals at a resolution of five minutes could be used to maximise the economic efficiency of the power system, revealing the true cost of electricity provision to consumers and thereby providing an economic signal to maintain the system balance. The use of price signals to this effect is termed indirect load control. At a time resolution exceeding five minutes, it was deemed that direct load control was required to ensure the stability of the system. This view is shared by Callaway and Hiskens [9]; however they prefer the use of direct control for all ancillary services as the system operator has greater certainty when demand is controlled directly rather than indirectly through a price signal where the price response must be predicted.

Fig. 1 shows a conceptual illustration of indirect and direct control. Under indirect control, the aggregator has limited information about the demand that is being controlled, and must estimate the price response of its demand portfolio. Prices are then issued to induce an expected response. Prices can be