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Research Paper

Critical kick-back mitigation through improved design of demand response ☆

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HIGHLIGHTS

- A detailed explanation of load kick-back caused by demand concurrency.
- A comprehensive investigation of three kick-back mitigation algorithms.
- A heat pumps-based DSR fleet is simulated to support a comparative analysis.
- Detailed understanding of DSR's flexibility (or saturation conditions) is a must.

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ABSTRACT

The energy sector is adopting a lot of intermittent renewable energy sources nowadays. In order to successfully integrate these renewable sources, demand side resources (DSR), in a demand response (DR) setup, are able to provide power system services by exploiting their flexibility in power consumption. Load kick-back effect describes a dynamic process that the total power consumption of a population of DSRs is higher than the expected value during the steady state after the activation of DR program, due to their temporary synchronous behaviors. For DR programs designed with little consideration of load kick-back, not only the potential value of DR is limited significant but also power system operation can be jeopardized even more. In addition to explaining the severity of kick-back effect through illustrative examples, this paper proposes several methods to mitigate the critical kick-back effect in DR while maintaining the expected value of DR. The proposed methods are applied to a DR program that aims at using thermostatically controlled heating of residential houses for peak shaving. Quality measures are adopted to measure the performance.

1. Introduction

Aimed at a more sustainable energy system, there is rapid growth of clean energy solutions connected to the existing power system infrastructure. At the supply side, the amount of intermittent renewable has been increased by almost 10 times in the last decade [1], if taking wind power as an example. At the end-user side, demand side resources (DSR), such as small wind turbines (WT), rooftop photovoltaic panels (PV), electric vehicles (EV), and heat pumps (HP) are also getting more and more recognizable [2]. Power system operation is significantly challenged by both trending developments with intermittent generation profiles and increased peak energy consumption respectively.

Demand response (DR) plays an essential role in integrating of renewable sources and DSRs. An import function achieved by DR is to mobilize the flexibility of controllable DSRs to actively participate in providing power system services. With supporting control and communication infrastructure, DSRs are capable to shift their energy production or consumption, such that they can be treated as intermediate energy storage with certain operating constraints [3–5]. *Flexibility* is referred to the flexible portion of their energy generation or consumption constrained by the primary applications and technical limitations. DR program is proposed for balancing the energy supply and demand [6,7] and solving the congestion problems [8–10] with various types of DSR technologies and control strategies. This paper is focused on realizing unscheduled DR services with real-time control strategies.

Load kick-back effect, a.k.a., "rebound effect", "pay-back effect" or "cold load pick-up" is originally referred to as the phenomena

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that load may exceed the level during the steady state before the outage during the system restoration [11]. Recently, it is also observed in some DR programs after the flexibility from DSRs is activated [12–14]. Load kick-back effect in DR programs will lead to bad quality of service delivery and failure in complying the contract. It may even create larger congestion problems in the power system. Therefore, it is important that such issue is taken good care of in a DR program to obtain its maximal value. A rebound peak in kick-back effect is because of all DSR units behave synchronously forced by the external control signal provided by the DR program and by their operating constraints. In [12], the EV fleet is instructed to charge when price is low. The new charging schedule introduces several peaks in a day. The author in [13] coordinates the consumption of water heaters to reduce the peak load. Although the original peak in the peak hours is reduced by switching off the water heaters, a new peak is created when the water heaters are reconnected to the network. Even worse case is found in [14]. By controlling the cooling setpoint of thermostatically controlled load in commercial buildings, DR program is able to reduce the heating and cooling load during the original peak hours, but kick-back load is even larger than the original peak value (green and purple curves in Fig. 1). Among various design of DR programs, kick-back effects happen mostly during the situation when an identical control signal (either in a form of control setpoints, incentive signals, or predefined control trajectories) is received by a population of DSRs and they react to the control signal in the same way.

To mitigate the critical kick-back peaks, the author in [14] tries to reduce the new peak by extending the curtailing period. However, specific technical constraints of thermostatic loads, such as room temperature bounds, are not well considered. A model of flexibility product is defined in [7], which characterizes the kick-back effect as a rebound curve. However, it is not explained in the article how this characteristic curve can be kept in a DR program. In other cases, such as [15,16], the loads are scheduled in advance to achieve the control goal. However, such control strategies strongly reply on the prediction of external inputs, and the prediction errors and unforeseen disturbances may lead to unsatisfactory results during the operation. In addition, unscheduled system service may also need DSRs to provide their flexibility. Therefore, this paper focuses on proposing a few methods on how a DR program coordinates DSRs in real-time to reach the control objective, in the meanwhile takes care of the kick-back effects. The methods described here are suitable for facilitating the flexibility product agreed between the power system service vendor, i.e. aggregator, and the DSRs of its flexibility portfolio.

The contribution of this work is two folded. Firstly, the dynamic process of load kick-back effect is illustrated to help readers understand how the kick-back peak is created among a population. An aggregation framework is used for enabling the DR program. The power system impact is also presented showing the severity of kick-back effect concerning the system safety and operational efficiency. Secondly, a few methods are proposed to mitigate critical load kick-back effect. The control performance is evaluated against performance measures. To achieve the goals, a model of air-source heat pump system is provided, and a DR service, peak shaving service is formulated in the paper. However, the methods can always be generalized for different kinds of DSR technologies and different DR services.

The reminder of the paper is structure as follows. Section 2 presents the models, aggregation framework, and the control setup in this work. In addition, an illustrative example of kick-back is described to explain the phenomenon. It is followed by Section 3 with a few solutions to kick-back mitigation. Simulation results are presented to show the performance. Section 4 take the simulation results and evaluate the performance of individual control solutions with performance metrics. The work is concluded in Section 5.

2. Kick-back effect

A population of homogeneous DSRs is coordinated by an aggregator to perform demand response, which is an interface between the power system operator and individual DSR units. The aggregation framework is presented in Fig. 2. The aggregator aggregates the flexibility from DSRs into a larger scale and responds to the requests from power system operator on mobilizing the flexibility. It is responsible for delivering the power system services in an agreed service quality, and communicates with all DSR units at their owners' premises. The DSR units can either be directly controlled by the aggregator, or react to an incentive signal derived from the system operating condition [5]. In this paper, both approaches are considered to enable DR programs. Residential houses heated by thermostatically controlled heat pumps are served as DSRs to be controlled in this work.

The DSR models and the detailed implementation of the aggregation setup between the aggregator and DSRs are elaborated in this section. In addition, the load kick-back effect and its impact on power system operation are illustrated.

2.1. Dynamic process

The black curve in Fig. 4 shows an aggregated dynamic behavior of a fleet of 70,000 thermostatically controlled heat pumps, which are used for heating up the residential buildings. The aggregated power profile is simulated using a bottom-up approach. The behaviors of individual heat pumps are characterized in the simulation, so as the associated residential houses. The thermal usage of a house are characterized by a first order dynamic model (see the Eq. (1)). The value of the indoor temperature T_{in} [°C] represents the amount of energy stored in the house. It is affected by the out-

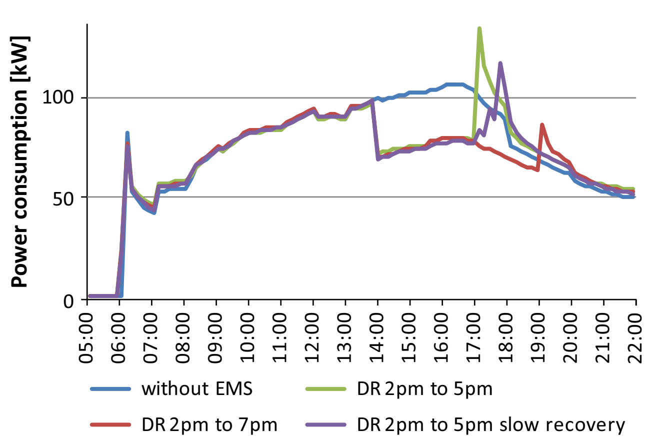

Fig. 1. Simulated HVAC peak load in a commercial building with and without DR during a summer day. Adapted from [14].

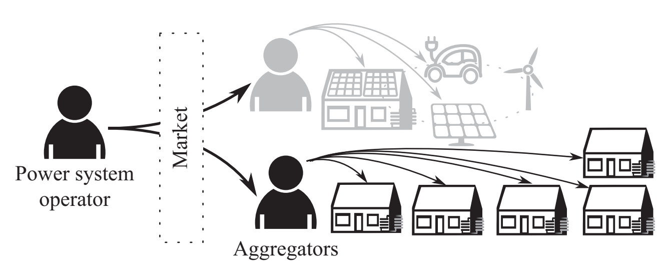

Fig. 2. A simple diagram of the aggregation framework.

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