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A new demand response scheme for electricity retailers

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ABSTRACT

A new demand response (DR) scheme from the retailers' point of view is presented in this paper. The proposed DR scheme allows a retailer to decide how to buy DR from aggregators and consumers. Various long-term and real-time DR agreements are proposed, where they are considered as energy resources of retailers in addition to the commonly used providers. These innovative agreements include pool-order options, spike-order options, forward DR contracts and reward-based DR. A stochastic energy procurement problem for retailers is formulated, in which pool prices and customers' participation in the reward-based DR are uncertain variables. The feasibility of the problem is assessed using a realistic case of the Queensland jurisdiction within the Australian National Electricity Market (NEM). The outcomes indicate the usefulness of the given DR scheme for retailers, particularly for the conservative ones.

1. Introduction

1.1. Literature review, contributions and approach

Demand response (DR) can play a vital role in alleviating market and network issues. While network providers employ DR to maintain the security and reliability of the network, mitigating the risk of pool price volatilities is the main aim of using DR by electricity retailers.

There are various papers focusing on DR. The basic definitions and classifications of DR programs are addressed in [1], where DR is divided into two main categories, namely incentive and price-based programs. The elasticity concept is introduced in [2], where it reflects the responsiveness of customers to price changes. Incentive-based DR programs are formulated in some papers such as [3–5]. Ref. [3] provides the mathematical formulations of DR programs. A coupon-based method is formulated in [4], where the incentive offered to consumers is determined according to the market price. An incentive-based scheme is presented in [5], in which both the energy cost and peak-to-average ratio are minimized through a game theory approach. Price-based DR actions are presented in many research articles such as [6,7]. Authors in [6] model a real-time DR, where consumers are able to adjust their energy usage based on real-time prices. A comprehensive time-of-use is formulated in [7], where the elasticity is modeled as a non-zero cross and flexible function. Technical aspects of DR are illustrated in several papers. For instance, detailed control strategies of managing electrical loads like water heater, air conditioners, space heating and cooling systems are provided in [8–12].

A new concept is introduced in [13,14], where DR is treated as a public good. Authors in [13] devise a DR Exchange, in which buyers and sellers trade DR in a pool-based market. This market is modified in [14], where a Walrasian market clearing technique is used instead of the former pool-based method.

Option valuation theories are used to evaluate the economic value of DR. Paper [15] formulates option values for three distinct DR programs, known as load curtailment, load shifting and fuel substitution. Consequently, customers can decide whether to invest in these DR programs. This option valuation is applied to the critical peak pricing program in [16,17]. Furthermore, a stochastic programming approach is proposed in [18], where industry customers can agree whether to accept a load curtailment option.

In line with retail markets, DR is a useful resource of hedging risk by retailers. However, few papers address this concept: authors in [19] use interruptible loads to alleviate the uncertainty of pool markets faced by a load serving entity. Two interruptible load contracts, pay-in-advance and pay-as-you-go, are evaluated in [20] as the energy resources of electricity retailers. Self-production is also used in [21] to limit the risk of cost fluctuations in pool markets. Ref. [22] uses interruptible loads as an energy resource of distribution companies. A short-term deterministic model is presented in [23], in which distribution companies can use interruptible loads to place bids in the market. Besides interruptible loads, real-time pricing and time-of-use are also offered by distribution companies to alter the energy usage of consumers [24].

Concluding the above background, the following points can be stated. (1) The majority of studies on DR focus on the basic concepts,

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Nomenclature

A. Constants

$d(t)$ duration of period t
$f_{po}^{pen}(t)$ penalty of not exercising pool-order option po during period t
$f_{so}^{pen}(t)$ penalty of not exercising spike-order option so during period t
$P_{f,b}^{DR,MAX}(t)$ upper limit of demand in the bth block of forward DR f during period t
$\bar{P}_{j}^{DR}(t)$ demand of the jth step of stepwise DR
$P_{f,b}^{MAX}(t)$ upper limit of demand in the bth block of forward contract f during period t
$P_{po}^{MAX}(t)$ upper limit of demand in pool-order option po during period t
$P_{so}^{MAX}(t)$ upper limit of demand in spike-order option so during period t
$P^{req}(t, w)$ required power by the retailer in period t
$PF(w, t)$ scenario-based participation factor
$\bar{R}_{j}^{DR}(t)$ upper limit of the jth interval of stepwise DR
β confidence level
ρ risk level
$\lambda_{po}(t)$ price of pool-order option po during period t
$\lambda_{f,b}^{DR}(t)$ price of the bth block of forward DR f during period t
$\lambda_{f,b}^{F}(t)$ price of the bth block of forward contract f during period t
$\lambda^{p}(t, w)$ pool-price scenario w during period t
$\lambda_{so}^{Str}(t)$ strike price of spike-order po during period t
$\pi(w)$ probability of scenario w

B. Numbers

N_{BDR} number of given blocks in forward DR
N_{F} number of forward contracts
N_{FB} number of forward contract's blocks
N_{FDR} number of forward DR contracts
N_{J} number of intervals in the reward-based DR
N_{po} number of pool-order options
N_{so} number of spike-order options

C. Variables

$C(FDR)$ cost of forward DR contracts
$C(F)$ cost of forward contracts
$C(PO)$ cost of pool-order options
$C(SP)$ cost of spike-order options
$EC(P)$ expected cost of the pool market
$EC(RDR)$ expected cost of reward-based DR
$P^{DR}(t)$ power bought from real-time DR in period t
$P_{po}(t)$ power bought from pool-order po in period t
$P_{so}(t)$ power bought from spike-order *so* in period t
$P_{f,b}^{DR}(t)$ power bought from the bth block of forward DR f
$P_{f,b}^{F}(t)$ power bought from the bth block of forward f
$P^{p}(t, w)$ power traded in the pool in period t and scenario w
$R^{DR}(t)$ reward offered by the retailer in period t
$R_{j}^{DR}(t)$ reward of the jth interval of stepwise DR
$v_{DR,j}(t)$ binary variable indicating if the jth interval of reward-based DR is applied in period t
$v_{po}(t)$ binary variable indicating if pool-order option *po* is exercised in period t
$v_{so}(t)$ binary variable indicating if spike-order option *so* is exercised in period t
$\eta(w)$ auxiliary variable for calculating CVaR
ζ auxiliary variable for calculating CVaR

formulations and technical aspects of DR. To our knowledge, only authors in [13,14] investigate a mechanism through which DR is traded as a commodity between its providers and buyers. (2) Though some papers address the financial option concept, they mostly assess DR valuations from a customers' point of view. There is no significant work investigating trading DR option contracts. (3) Less attention has been paid to the applicability of DR by electricity retailers, where among all DR, mostly the interruptible load program is considered.

Considering these highlights, the contributions of this paper are summarized as follows.

Firstly, this paper proposes a new DR scheme in which DR is treated as a public good. The proposed scheme differs from that of [13,14] in two main directions. (1) In the proposed method, DR is directly traded between its providers and buyers. (2) The proposed scheme involves various DR agreements which cover both long-term and short-term actions: A forward DR contract is proposed through which DR is traded in a certain volume and price for a given period. In addition, by adapting the well-known financial option concept [25,26], two distinct DR options are proposed here: pool-order and spike-order options. While pool-order options are useful to hedge against small deviations of pool prices, spike-order options are employed during price spikes. These DR options are mathematically formulated in this paper. Finally, a reward-based DR [27] is considered as a real-time resource in the proposed DR scheme. According to this DR, the volume of load reduction increases as higher incentives are offered by the retailer. This DR is modeled stochastically, where the unpredictable behavior of consumers is modeled through a scenario-based participation factor.

Secondly, the developed DR scheme is modeled as the energy resource of electricity retailers. This scheme allows retailers to decide how to procure various DR agreements from aggregators or large consumers. Retailers are able to purchase DR through secure contracts (forward DR). They can also set DR option agreements (pool-order and spike-order options) which their exercising depends on the pool market volatilities. Finally, they can rely on real-time DR (reward-based DR) of which its outcome is influenced by customers' behavior.

The effectiveness of the proposed DR scheme is evaluated on an energy procurement problem, in which the retailer aims to minimize its energy cost while maintaining its desired risk level. It is assumed that the retailer employs DR in addition to forward contracts and pool markets. A stochastic programming approach is formulated, where pool prices and customer's behavior are considered as uncertain variables. The risk is modeled by conditional value-at-risk (CVaR). The problem is analyzed on a realistic case of the Queensland region within the Australian NEM.

1.2. Motivations in the Australian NEM

In Australia, several trial DR programs have been implemented by market entities such as network service providers as well as electricity retailers. Nevertheless, DR is still in its early stage in the NEM. This is derived from many challenges such as customers' unwillingness to participate in DR, the lack of enough knowledge and training, the lack of proper metering facilities (smart metering) and market barriers such as market policies and registration fees.

The peak growth rate has become worse in the NEM over the past few years. Between 2005 and 2011, the peak growth rate was about four times higher than that of energy growth [28]. The Australian government estimated that 25% of retail electricity costs come from peak events even though they occur for a period of less than 40 h a year [28]. Note that the peak demand has been decreased from 2011 to 2012. This decrement trend is due to several factors, where global recession, high penetrations of roof-top PV and a mild summer are deemed to be the main reasons [29].