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Designing interruptible load management scheme based on customer performance using mechanism design theory

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A B S T R A C T

Interruptible load management (ILM), as an important incentive-based demand response (DR) program, plays a critical role in power system operation. An improved ILM scheme design method is proposed in the paper. From the perspective of social welfare, the scheme design is described as an optimization problem, and then mechanism design theory is adopted for solving. The novel idea presented in the paper is that the customer baseline load (CBL) is used to parameterize the type of customer (TOC), which is fundamental information for application of mechanism design theory. Being private information, TOC is not directly attainable, but CBL can be estimated based on historical load data (namely the customer performance), and it can reflect the customers' rational judgments in self-benefit decisions. Firstly, the validity of adopting CBL to determine TOC is demonstrated. Then, the load curtailing potential constraints and the objective function are rebuilt in the expression of CBL correspondingly, so that the mechanism design theory successfully works with CBL instead of TOC. Moreover, adjustment strategies are also proposed to cope with the possible unenforceable scheme scenarios, thus the practicability of the designed scheme is ensured. Finally, simulations are carried out to validate the effectiveness of the proposed method.
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1. Introduction

The development of power system faces with two challenges, one is the uncertainties caused by renewable energy integration and electricity market competition, and the other is the urgency for energy efficient utilization due to the exhaustion and pollution of fossil fuel. Both challenges exacerbate the power system's security and stability, therefore various demand response (DR) programs including interruptible load management (ILM) are widely deployed to relieve the stress [1,2].

The ILM, as an important regulation mean, could be implemented in several modes. One mode is the real-time dispatch [3–5], in which the interruptible load (IL) and the generation are co-scheduled according to the safety and economy of the power system. Meanwhile the interrupted loads are awarded by the real-time price (RTP). Nowadays this mode has become an important measure to improve the accommodation of intermittent wind generation [6]. Another mode is bilateral contract, which is signed between the utility and its customers. The customers interrupt or curtail load actively or controllably according to utility commands when power system emergency occurs, and then they are compensated on the basis of contracts [7]. Generally, the former mode employs electric vehicles (EVs) [8], heating ventilation and air conditionings (HVACs) [9], even residential appliances [10] etc. as means, while the latter mode involves large industrial and commercial customers as participants. As long as the customers are willing to cooperate, ILM can work both in the monopoly and market environments. ILM contracts are usually implemented based on a scheme designed in advance [11,12]. In China, the grid utility possesses the obligations of power transmission and distribution simultaneously. In such condition, when the utility needs to design ILM scheme, some objective information such as the historical load data is easy to acquire, but some subjective information such as the type of customer (TOC) is not directly attainable, consequently this becomes the obstacle to be overcome.

During the generation shortage period, ILM helps the utility to acquire resources timely to cope with the imbalance between supply and demand. If sufficient private information is attained, the ILM scheme can be designed by an optimization way [13,14], results in reasonable and explicit contracts. Unfortunately, in reality, there exists information asymmetry between the utility and its customers. In general, it is rather difficult to obtain private information for the sake of market strategies [15]. Moreover, rational customers always behave to maximize their own expected

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Nomenclature

Abbreviations
CBL customer baseline load
DFT discrete Fourier transform
DR demand response
EI equilibrium information
EV electric vehicle
HVAC heating ventilation and air conditioning
IL interruptible load
ILM interruptible load management
RTP real-time price
TOC type of customer
VOLL value of lost load

Parameters
$K_{1,i}/K_{2,i}$ quadratic/linear term coefficient of outage cost function
$\theta/\hat{\theta}$ real/lying TOC
λ_L equality constraint Lagrange multiplier
ω customer willingness parameter
γ saturation point parameter

Variables
C outage cost
C_V equilibrium coverings
E load curtailing potential
$f_{customer,i}$ benefit of customer i
$F_{customer}$ customer benefit
$F_{society}$ social welfare
$F_{utility}$ utility benefit
h_i result function: load curtailing amount for customer i
h_π result function: compensation price
H benchmarking function
MC marginal outage cost
MU marginal utility
n total customer number to participate in the ILM scheme
P load demand
P_{CBL} calculated customer baseline load
P_{min} announced minimum security capacity
q load curtailing amount
U utility function
ΔM error of CBL calculation model
ΔP total expected amount of curtailing load
ΔR customer response deviation
α benchmark value
β value of lost load
π compensation price
ε load curtailing potential uncertainties

Matrices and vectors
$\boldsymbol{F}$ load curtailing amount
$\boldsymbol{g}$ equilibrium information functions
$\boldsymbol{h}$ result functions
$\boldsymbol{m}$ equilibrium information
$\boldsymbol{m}^*$ global equilibrium information
$\boldsymbol{\Omega}$ parameter space

benefits, so they may not follow the scheme as designed [16,17]. Thus, low efficiency of ILM scheme design is inevitable.

In circumstance of free choice, voluntary exchange, information asymmetry and decentralized decision making, can resources be effectively allocated at the least information cost? Mechanism design theory has given an answer [18]. As a part of the game theory, it was widely used in related economic and social fields including law, political science, psychology, etc. [19]. More specifically, it had been applied to the mechanism design of pool-based electricity market [20,21], market [22] and bilateral market between the large customers and the generators [23]. All these applications show that mechanism design theory is promising in solving the problems of poor effectiveness of information observation and communication, and high complexity of computation.

When designing the ILM scheme, mechanism design theory makes sure that the utility's benefit is maximized and that its customers are compensated sufficiently to participate voluntarily. To apply mechanism design theory to the ILM scheme design, Ref. [24] introduced continuous TOC into the customer outage cost function, and determined an ILM contract suitable for different types of customers. Ref. [25] proposed an improved method to calibrate customer demand management behavior by using utility information, and formulated the ILM contract model with discrete TOC. But neither considered the customer maximum IL limit, so further improvements were made in [26]. Ref. [26] assumed that the TOC obeyed a certain probability distribution, and the maximum IL could be expressed with specified intervals. Conclusions can be drawn that the TOC, as a parameter to characterize the customer performance in DR, is significant in these studies mentioned above. Despite that the TOC was estimated based on existing utility data in Ref. [25], the physical meaning of this parameter was still vague, and that restricted its application to some extent. Ref. [27] presented a method to evaluate the customer performance in DR by the customer baseline load (CBL) which can be estimated based on historical load data. Actually, the CBL is extensively used in American electricity market to evaluate the DR effects [28], and it is clearly stated and conveniently calculated. So it will be more understandable and well-founded to design ILM scheme based on CBL. In addition, few researches focuses on the scheme enforcement problem related to the load curtailing potential constraints [29,30], thus the practicability of the designed scheme is partly limited.

On the basis of previous researches, the remainder of this paper is organized as follows. Section 2 proposes an ILM scheme design model with the objective of maximizing social welfare. After a preliminary analysis of the CBL, the load curtailing potential constraints and the objective function are rebuilt in the expression of CBL correspondingly in Section 3. Section 4 illustrates the basic principles of mechanism design theory and the ILM scheme design steps. Two scenarios are simulated and analyzed in Section 5. Finally, Section 6 concludes this paper.

2. ILM scheme design model

We shall explicate some essential assumptions before start:

(1) The customer is rational enough, which means that he will arrange the load at his maximum individual utility. Meanwhile the real CBL at each period must reflect his maximum utility demand.
(2) Maximizing benefit is the motive of customers' behaviors, which drives customers to respond to the load curtailing scheme and report his result of the equilibrium information (EI) function, so that other factors which may have influences on response uncertainties need not to be taken into consideration.

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