Multi-stage Coupon Incentive-based Demand Response In Two-settlement Electricity Markets

Haiwang Zhong, *Member, IEEE*, Le Xie, *Member, IEEE*, Qing Xia, *Senior Member, IEEE*, Chongqing Kang, *Senior Member, IEEE*, and Saifur Rahman, *Fellow, IEEE*

***Abstract*—This paper extends our recent work and proposes a multi-stage coupon incentive-based demand response (M-CIDR) in two-settlement electricity markets. In contrast to the real-time pricing (RTP) or critical peak pricing (CPP) demand response programs, M-CIDR continues to offer a flat rate to retail customers and additional voluntary incentives to induce demand response. Compared with single-stage CIDR, a unit commitment model is employed so that the inter-temporal constraints can be considered conveniently. Theoretical analysis shows the benefits of the proposed scheme in two-settlement electricity markets. And numerical illustration is performed in the IEEE 30 bus system. The results show that during the periods with price spikes, the proposed M-CIDR can effectively induce demand response, reduce market clearing prices, obtain a social welfare which is close to that in the RTP scheme.**

***Index Terms*—Multi-stage Coupon Incentive-based Demand Response (M-CIDR),Two-settlement System, Real-Time Price (RTP), Smart Grid Communication, Electricity Markets.**

Nomenclature

Constant

G	Number of generating units
N	Number of consumers
T_i^{on}	Minimum up time of unit i
T_i^{off}	Minimum down time of unit i
SC_i	Startup cost of generator i

Variable

P_{gi}	Output of generator i
P_{gi}^{max}	Maximum output of generator i
P_{gi}^{min}	Minimum output of generator i
P_d	Total demand in the wholesale market
ΔP_d	Total demand response in the wholesale market
ΔP_{di}	Demand reduction of consumer i
$P_{di,0}$	Baseline of consumer i
P_{di}	Power consumption of consumer i
π_{RTP}	Real-time price in the wholesale market
π_{RR}	Retail rate of electricity
$\pi_{WTP,i}$	Willingness to pay of consumer i
π_c	Coupon price in the retail market
y_i	Utility of consumer i
$b_{i,k}$	Intercept of segment k of consumer i's utility function
$S_{i,t}$	Startup cost of generator i at period t
P_{DA}	Day-ahead cleared electricity
π_{DA}	Market clearing price in day-ahead markets
$X_i^{on}(t)$	Time for which unit i has been on at period t
$X_i^{off}(t)$	Time for which unit i has been off at period t
$\alpha_{i,t}$	Commitment state (1 or 0) of unit i at period t

Function

$g_i(\cdot)$	Response function of consumer i
$C_i(\cdot)$	Operating cost function of generator i
$U_i(\cdot)$	Utility function of consumer i

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H. Zhong, Q. Xia and C. Kang are with State Key Lab of Power Systems, Dept. of Electrical Engineering, Tsinghua University, Beijing 100084, China. (e-mail: zhonghw@tsinghua.edu.cn, qingxia@tsinghua.edu.cn, cqkang@tsinghua.edu.cn).

L. Xie is with Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX. (e-mail: lxie@ece.tamu.edu).

S. Rahman is with Advanced Research Institute, Virginia Tech, Arlington, VA. (e-mail: srahman@vt.edu).

I. Introduction

With the integration of more and more intermittent renewable generation such as wind and solar, well designed and deployed demand response (DR) can bring significant system-wide benefits in terms of ensuring power system security and improving economic efficiency [1]. Various DR programs have been proposed in existing literature. Price-based DR programs include time-of-use pricing (TOU), real-time pricing (RTP) and critical peak pricing (CPP) [2], etc. Incentive-based DR programs include interruptible load contract (ILC) [3], direct load control (DLC), peak time rebate (PTR) [4], and demand side bidding [5] etc. A new type of incentive-based DR program referred to as coupon incentive-based demand response (CIDR) was recently proposed in [6], [7].

In CIDR, load serving entities (LSEs) could induce retail customers to reduce non-essential electricity use *voluntarily* at times when real-time price spikes are likely to occur by providing the consumers with coupons via the near-real-time smart grid communication.

For the sake of simplicity, it was assumed in [7] that all the electricity was settled in the real-time market. However, the reality is that most independent system operators (ISOs)/regional transmission organizations (RTOs) operate both the day-ahead market and the real-time market; this is well known as the two-settlement system [8]. And in the two-settlement system:

1) All electricity transactions in the day-ahead energy market are settled at the day-ahead locational marginal prices (LMPs).

2) The hourly schedules and day-ahead LMPs in the day-ahead market are merely financially binding.

3) The real-time market is based on actual real-time operating conditions of the power system.

4) All electricity transactions in the real-time market are settled at the real-time LMPs.

Take ISO-NE and California ISO as examples, the energy cleared in the real-time market is around 2%∼8% [9], [10]. This seemingly small percentage of real-time transacted energy implies major business opportunities in the electricity market. Therefore, LSEs would manage their energy portfolio by purchasing most of the energy in the day-ahead market to hedge the risks of price volatility in the real-time market.

Hence, the single-stage model considering only the real-time electricity market [7] could not reveal the true benefits of CIDR in the real world. In addition, the real-time price spikes may last for several periods in reality due to the change of the weather or the outage of a generating unit. It's not enough to issue the coupon in only one period.

Therefore, built upon our recent work in [6], [7], multi-stage coupon incentive-based demand response(M-CIDR) is proposed in this paper. This paper advances the CIDR further to include the following:

1) The single-stage model is extended to a multi-stage model to incorporate both the day-ahead and real-time market.

2) A unit commitment model is employed to clear the day-ahead electricity market.

3) The cost-benefit analysis is based on two-settlement systems, which is closer to reality.

The salient advantages of M-CIDR compared with CIDR are:

1) Inter-temporal constraints of units can be considered in the M-CIDR, such as the minimum up/down time constraints of units. This is closer to the day-ahead market operations in reality.

2) The optimization is not based on instant power but the energy within a time horizon. The LSE's and the consumer's objectives are targeting the benefits within a time horizon.

3) The deferrable load can be considered in the M-CIDR conveniently, while it cannot be modeled in the single-stage CIDR. And this will be investigated in our future work.

In M-CIDR, based on the very short-term load forecast and wind power forecast, LSEs can issue coupons in the periods when there is a sudden wind ramp or a price spike. The coupon prices in different periods can be different. The details of coupon pricing algorithm can be found in [7].

II. Analysis of M-CIDR in Two-settlement Electricity Markets

The true benefit of the M-CIDR in two-settlement electricity markets will be evaluated in this section. For the sake of clarity, the subscript t is dropped temporarily in this section.

A. Day-ahead Market

The day-ahead market is cleared based on the generation offers and demand bidding. The market clearing procedure is illustrated in Fig. 1. For an LSE, the profit in the day-ahead market can be expressed as follows:

$$\pi_{RR} P_{DA} - \pi_{DA} P_{DA} \tag{1}$$

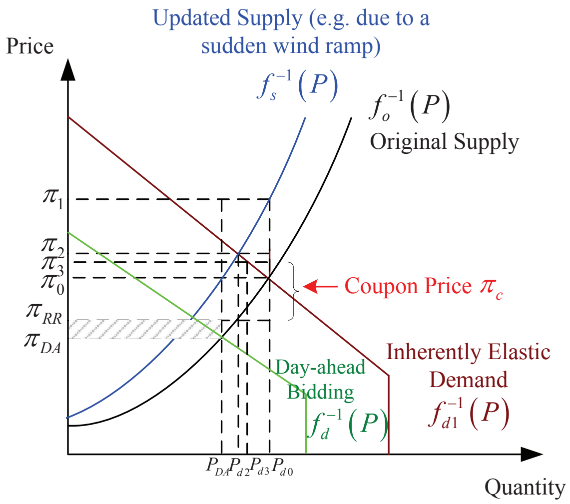

Fig. 1. The Illustration of M-CIDR in Day-ahead and Real-time Markets

The first term is the retail revenue, and the second term is the purchasing cost. Due to the sufficient competition among participants in the day-ahead market, π_{DA} is relatively low, typically, lower than the retail rate π_{RR}. In other words, the LSE is profitable in day-ahead market transactions. The shaded part in Fig. 1 shows the LSE's profit in day-ahead markets.

B. Real-time Market

In real-time operations, more accurate information becomes available. Several conditions may vary compared with the day-ahead forecast. For instance, the day-ahead system load forecast error ranges from 1% to 3% whereas the day-ahead wind forecast error ranges from 10% to 20% [11]. These errors would cause the price fluctuation in the real-time market.

The difference between the real-time load P_{d0} and the day-ahead cleared energy P_{DA} (only financially binding) originates from the system load forecast error, wind forecast error and LSEs' bidding strategies. The LSE cannot foresee exactly how much energy they should buy in the day-ahead market when they submit the bidding curves.

For the sake of simplicity, the day-ahead bidding curve is assumed to shift towards the right. The slopes of the demand curves are the same.

1) Reference Scenario: If the day-ahead wind forecast is perfect and there is no sudden wind ramp, the LSE's profit in the two-settlement system can be stated as follows:

$$(\pi_{RR} - \pi_{DA}) P_{DA} + \pi_{RR}(P_{d0} - P_{DA}) - \pi_0 (P_{d0} - P_{DA}) \tag{2}$$

π_0 is the real-time price of electricity.

If there is a sudden wind ramp, the following three scenarios are considered in this paper.

2) Flat Rate Scenario: In this scenario, the demand is assumed to be inelastic. The wholesale price will become π_1.

$$(\pi_{RR} - \pi_{DA}) P_{DA} + \pi_{RR}(P_{d0} - P_{DA}) - \pi_1 (P_{d0} - P_{DA}) \tag{3}$$

If the wind ramp is large, π_1 would be much higher than π_0, appearing as a price spike.

3) Real-time Price Scenario: In this scenario, consumers are exposed to the RTP and assumed to respond to the RTP based on their own willingness-to-pay. The wholesale price will become π_2 and the quantity will decrease to P_{d2}.

$$(\pi_{RR}-\pi_{DA})P_{DA}+\pi_{RR}(P_{d2}-P_{DA})-\pi_2(P_{d2}-P_{DA}) \quad (4)$$

4) M-CIDR Scenario: In this scenario, consumers are incentivized by LSEs to reduce their power consumption. The intersection point in this scenario is assumed to be (P_{d3}, π_3).

The LSE's profit can be expressed as follows:

$$(\pi_{RR}-\pi_{DA})P_{DA}+\pi_{RR}(P_{d3}-P_{DA})- \\ \pi_3(P_{d3}-P_{DA})-\pi_c(P_{d0}-P_{d3}) \quad (5)$$

The relationships between P_{d3} and P_{d2}, between π_3 and π_2 are uncertain. They depend on the coupon prices and consumers' demand response.

III. Mathematical Formulations

The proposed M-CIDR scheme is formulated with a multi-stage model of both the day-ahead and real-time electricity market. The coupon price within a period is assumed to be uniform for all retail customers.

A. ISO/RTO

The ISO/RTO is in charge of clearing the electricity market. The objective is maximizing the social welfare within a time horizon.

Objective function:

$$\max_{P_{gi,t},P_{di,t}} \sum_{t=1}^{T}\sum_{i=1}^{G}[U_i(P_{di,t})-\alpha_{i,t}C_i(P_{gi,t})-S_{i,t}] \quad (6)$$

Subject to:

$$\sum_{i=1}^{G}P_{gi,t}=\sum_{j=1}^{N}P_{dj,t},\ t=1,2,\dots,T \quad (7)$$

$$\alpha_{i,t}P_{gi}^{min}\le P_{gi,t}\le \alpha_{i,t}P_{gi}^{max},\ i=1,2,\dots,G \quad (8)$$

$$P_{di}^{min}\le P_{di,t}\le P_{di}^{max},\ i=1,2,\dots,D \quad (9)$$

$$(X_i^{on}(t-1)-T_i^{on})*(\alpha_{i,t-1}-\alpha_{i,t})\ge 0 \quad (10)$$

$$(X_i^{off}(t-1)-T_i^{off})*(\alpha_{i,t-1}-\alpha_{i,t})\ge 0 \quad (11)$$

$$S_{i,t}\ge(\alpha_{i,t}-\alpha_{i,t-1})*SC_i \quad (12)$$

$$S_{i,t}\ge 0 \quad (13)$$

The demand curve is assumed to be a staircase shape, and the utility function of consumer i is a concave m-segment piecewise linear function [12].

$$U_i(P_{di})=\begin{cases}\pi_{WTP,i}^{1}P_{di}+b_{i,1}, & 0\le P_{di}\le P_{di}^{1}\\ \pi_{WTP,i}^{2}P_{di}+b_{i,2}, & P_{di}^{1}\le P_{di}\le P_{di}^{2}\\ \vdots, & \vdots\\ \pi_{WTP,i}^{m}P_{di}+b_{i,m} & P_{di}^{m-1}\le P_{di}\le P_{di}^{m}\end{cases} \quad (14)$$

The sequence of points $(\pi_{WTP,i}^{k}, P_{di}^{k}), k=1,2,\dots,m$ locate in the demand curve. $b_{i,k}, k=1,2,\dots,m$ is the intercept of segment k of the utility function.

B. LSE

As profit-seeking participants, LSEs' objectives are to maximize their expected profits within a time horizon.

Objective function:

$$\max_{\pi_{c,t}} E\{\sum_{t=1}^{T}[\pi_{RR}(P_{d,t}-\Delta P_{d,t})- \\ \pi_{RTP,t}(P_{d,t}-\Delta P_{d,t}-P_{DA})-\pi_{c,t}\Delta P_{d,t}]\} \quad (15)$$

Subject to:

$$\Delta P_{d,t}=\sum_{i=1}^{N}\Delta P_{di,t},\ t=1,2,\dots,T \quad (16)$$

$$\Delta P_{di,t}=g_{i,t}(\pi_{c,t}),\ t=1,2,\dots,T \quad (17)$$

The first term in the objective function is the retail revenue, the second term is the purchasing cost in the wholesale real-time market, and the last term is the coupon payment to consumers. Compared with [7], only the difference between the actual load and the day-ahead cleared load is settled at the real-time prices.

The function $g_{i,t}(\pi_{c,t})$ reflects the response behavior of consumer i at period t when he/she is offered the coupon price $\pi_{c,t}$.

In general, $g_{i,t}(\cdot)$ may not be expressed in closed forms, and can be obtained through the decision making process mentioned below in (18)-(19).

C. Consumer

Retail customers are assumed to be rational participants. The consumers' objectives are to maximize their own surplus within a time horizon.

Objective function:

$$\max_{P_{di,t}} \sum_{t=1}^{T}[y_{i,t}-\pi_{RR}P_{di,t}+\pi_{c,t}(P_{di,t,0}-P_{di,t})] \quad (18)$$

Subject to:

$$y_{i,t}\le \pi_{WTP,i,t}^{k}P_{di,t}+b_{i,k},\ k=1,2,\dots,m \quad (19)$$

$P_{di,t,0}$ is the baseline of consumer i at period t. $y_{i,t}$ is the auxiliary variable denoting the utility of consumer i at period t. As long as the sum of electricity bill savings and the coupon incentives from LSEs outweighs the lost benefit, consumers are assumed to respond to the coupon incentives. The higher the coupon price is, the greater the number of consumers who will respond to the incentives. $\Delta P_{di,t}=P_{di,t,0}-P_{di,t}$ will then be submitted to LSEs for them to make the decision in real-time markets.

IV. Numerical Case Study

In this section, the performance of the proposed M-CIDR scheme is evaluated in the IEEE 30 bus system. The supply and demand data are obtained from ERCOT [13].

The load profile and the wind power output in ERCOT is shown in Fig. 2. They are then scaled down to fit the IEEE 30 bus system. It is assumed that there is a sudden wind power

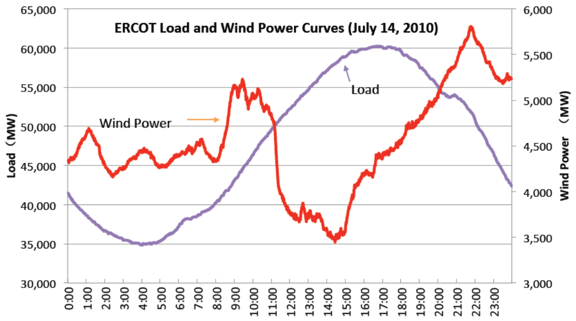

Fig. 2. The Load Profile and Wind Power Output of ERCOT [14]

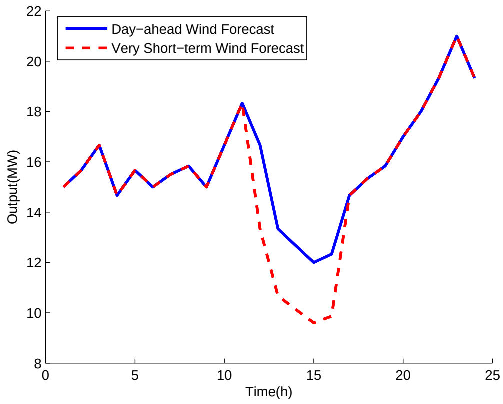

Fig. 3. The Wind Power Forecast Error in Near Real-time

TABLE I
ENERGY MIX OF THE IEEE 30 BUS SYSTEM

	Natural Gas	Coal	Wind	Nuclear
Capacity(MW)	150	55	30	15

ramp down at 8 a.m.. And from 8 a.m. to 12 a.m., the wind power is less than the day-ahead forecast by 20%, which is shown in Fig. 3.

The generation mix in [15] is scaled down and shown in Table I.

In the numerical experiments, it is assumed that 92% of actual load has already been cleared in the day-ahead market. The shape of the supply and bidding curve is a staircase. For the sake of the simplicity, no transmission congestion is considered.

All the programs are written in C language, and the optimization problems are solved by the CPLEX solver [16].

A. Case Setup

Four cases are considered as follows. In Case 1, it is assumed that the wind power forecast in day-ahead is perfect. There is no sudden wind ramp in real-time operations; in Case 2, 3, and 4, it is assumed that there is a sudden wind power ramp down in near real-time.

1) Reference Case: For the sake of simplicity, the consumer baseline levels for all the other cases are set at the actual demand levels of the reference case.

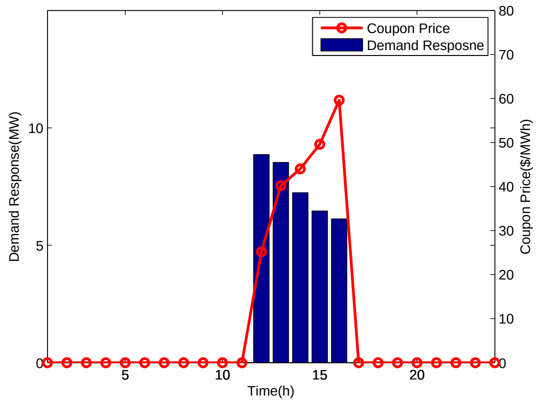

Fig. 4. Coupon Prices and Demand Response in The Real-time Market

2) Flat Rate: Consumers' inherent demand flexibility is not utilized due to the flat electricity retail rate. This case represents the status quo in which consumers do not have any incentive to respond to price signals in the electricity market. This serves as a benchmark against which the performance of other cases is evaluated.

3) RTP: Consumers are exposed to the wholesale RTP. It is assumed that all consumers will respond to the wholesale RTP based on their respective willingness-to-pay.

4) M-CIDR: Consumers still enjoy a flat retail rate whereas the demand reductions are paid by LSEs at coupon prices. It is assumed that consumers will respond to the coupon incentives based on their own willingness-to-pay.

B. Result Analysis

Table II summarizes the results for all the cases.

1) LSE's Profit: Due to the design of two-settlement systems, the LSE's retail revenue and profit in the day-ahead market is determined. For the RTP case, since the risk is transferred to retail customers, the LSE's profit in short-term operations is zero (although the LSE has a certain rate of investment return on an annual or multi-year basis).

As one can observe, the real-time profit of LSEs is negative, meaning that the LSEs suffer financial losses. By implementing the M-CIDR strategies, the LSEs' financial losses in the real-time market are reduced significantly.

2) Coupon Prices and Demand Response: The coupon prices and the demand response are shown in Fig. 4. The results show that during the periods with sudden wind change, effective demand response can be induced by the coupon incentives.

3) Market Clearing Prices: The market clearing prices are shown in Fig. 5. As one can observe, the market clearing prices in the flat rate case are highest, while they are lowest in the M-CIDR case.

4) Social Welfare: In terms of social welfare, the M-CIDR case obtains a social welfare quite close to that in the RTP case, whereas the social welfare in the flat rate case is lowest.

TABLE II
COMPARISONS OF THE DIFFERENT SCHEMES

	Case 1: Reference Case	Case 2: Flat Rate	Case 3: RTP	Case 4: M-CIDR
Day-ahead purchasing cost($)	366712	366712	366712	366712
Day-ahead retail revenue($)	434139	434139	366712	434139
Day-ahead profit($)	67427	67427	0	67427
Real-time purchasing cost($)	38758	46493	37035	32739
Real-time retail revenue($)	37751	37751	37035	33440
Real-time profit($)	-1007	-8742	0	-869
Coupon Payment($)	0	0	0	1570
Social Welfare($)	557410	554452	555547	555215

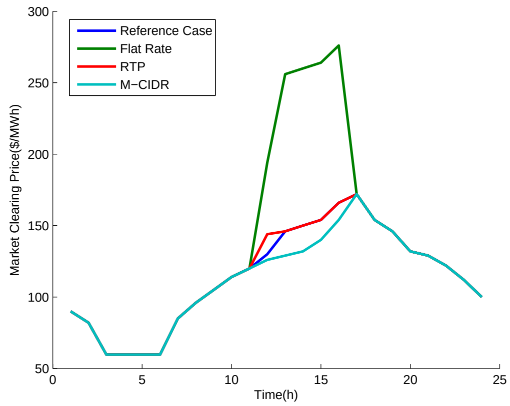

Fig. 5. Market Clearing Prices in The Real-time Market

V. CONCLUSION

We propose a multi-stage coupon incentive-based demand response (M-CIDR) in two-settlement electricity markets. In the proposed scheme, the retail customers' inherent flexibility is utilized while, at the same time, a basic flat rate structure is maintained. Inter-temporal constraints can be considered conveniently in the proposed model. Theoretical analysis and numerical case study reveal the true benefit of M-CIDR in two-settlement electricity markets. In M-CIDR, demand response can be effectively obtained, market clearing prices are reduced and a social welfare which is quite close to that in the RTP scheme can be acquired as well.

The differentiation of coupon incentives among different types of consumers and the inclusion of deferrable loads will be investigated in our future work.

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