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Model Price Responsive Demand in PJM Wholesale Market

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SUMMARY

One of the major key wholesale market competition strategies proposed by Federal Energy Regulatory Commission (FERC) is to promote demand response resources as a source of energy and ancillary services (AS). As the third generation in the development of DR programs, price responsive demand (PRD) refers to the process by which residential and small commercial consumers voluntarily adjust their consumption according to dynamic retail price changes. From the perspective of RTOs/ISOs, significant penetration of PRD will also bring about substantial benefits to operational reliability, system planning and market operation.

In 2011, PJM and ALSTOM Grid launched a PRD project to integrate PRD in the complete suite of PJM markets and business processes. Most of the technical software has been operated in the PJM production environment since May 15th 2012.

This paper focuses on the integration of the PRD model into the PJM RT market and studies to evaluate the impact of PRD behavior on the market.

KEYWORDS

Smart grid, demand response, price responsive demand, system operations, electricity market

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I. Introduction

With the investment in Advanced Metering Infrastructure (AMI) from Smart Grid (SG) initiatives, the amount of end customer demand with the capability to respond to wholesale electricity prices, or Price Responsive Demand (PRD), is increasing. As the third generation Demand Response (DR) programs, PRD refers to the process by which residential and small commercial consumers voluntarily adjust their consumption according to dynamic retail price changes[1]. As a major program in the smart energy demand component, PRD has the capability to deliver the majority of SG benefits, such as: reducing peak demand, shifting usage to off-peak hours, lowering total energy consumption and enabling consumers to manage their electricity usage and minimize their costs. PRD market rules have been accepted in PJM by the Federal Energy Regulatory Commission (FERC).

From the perspective of RTOs/ISOs, significant penetration of PRD could bring about substantial benefits to system planning, operational reliability, and market efficiency [2]. On the other hand, continuing to treat all demand in the traditional way, RTOs/ISOs will face increased operational uncertainty that will lead to less efficient market outcomes necessary to offset increased operational reliability risk.

In 2011, PJM and ALSTOM Grid launched a PRD project to integrate PRD in the complete suite of PJM markets and business processes that include the Reliability Pricing Model capacity market, Day-ahead market, Ancillary Service (AS) markets, Look Ahead (LA) Security Constrained Economic Dispatch (SCED) and Real-time (RT) market. Most of the technical software has been operated in the PJM production environment since May 15th 2012.

This paper focuses on the integration of the PRD model into the PJM RT market and studies to evaluate the impact of PRD behavior on the market.

II. Impact of PRD on PJM RT Business Process [3]

Currently, a Real-Time Security Constraint Economic Dispatch (RT SCED) program is used in PJM production to clear the RT energy market. The RT SCED provides dispatch instructions for the next 5 minutes, typically with a 10 min look-ahead window. Based on the latest AS and energy commitment decisions and AS assignments from inflexible resources, the RT SCED will dispatch energy and the rest of AS requirements. RT SCED sends out dispatch signals to market participants. It also provides the Locational Marginal Price (LMP) and AS market clearing prices (MCP). The RT SCED however, does not control the PRD in the sense that it does not send PRD a MW dispatch signal. Rather, PRD reacts to the LMPs based on the individual customer’s willingness to pay its resulting dynamic retail rate.

High LMPs may be caused by exhaustion of lower cost online resources, either on a system-wide basis or on a locational basis due to transmission congestion. The higher LMPs cause PRD loads to reduce their consumption. This avoids the need to dispatch more expensive resources in order to maintain power balance while respecting active transmission constraints. This results in a more efficient local and system wide dispatch solution.

From the perspective of AS market operation, the response of PRD will result in less load on the system, allowing additional resources to be available to provide frequency regulation and reserves. This will reduce AS MCPs, and help the system mitigate the severity of or even defer or eliminate the occurrence of reserve shortages and the resulting emergency conditions.

III. PRD features

The PRD works by reducing load consumption. The consumers will adjust their load based on the price they are willing to pay. With a dynamic retail tariff that reflects the LMP based wholesale price, the submitted demand response curve represents the demand reduction that would occur when the LMP is high. The modeled features of the PRD are described in below sections.

A. Demand Response Curve and Response Range

For each PRD load, the demand response curve shall be at the pricing node (pnode) level, and one curve for each hour. The curve can be stepwise or linear. Price and MW quantity are inversely related, which results in a downward profile. This represents that with the increase of dynamic price, the amount of energy consumption PRD is willing to reduce.

A typical stepwise demand response curve is illustrated in Fig. 1, which usually includes up to 10 steps. The curve shall be defined within the range of PRDMin and PRDMax, where PRDMin represents the minimum load MW value that a PRD load can be reduced to, PRDMax is the maximum load level of the PRD load. Here, it is assumed that PRDMax is the original load forecast value of the PRD load.

When activated, a PRD load is expected to respond within the response range.

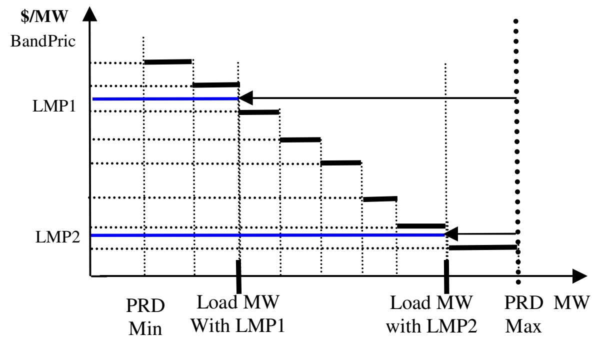

Fig. 1. Response of PRD to LMPs

B. PRD Response Model and Compliance Degree

For a PRD load, the load response will follow the demand response curve. The higher the LMP is, the more load MW will be reduced from the original load forecast of the PRD. The PRD is allowed to set the market clearing price. For a PRD load with a linear price curve, the load MW change will be smooth within the range. PRD loads with stepwise curves shall respond in blocks. That is, a block or blocks of load shall be switched off/on in response to price changes. The load MW change depends on the band width of demand response curve bands, as shown in Fig. 1.

The compliance degree of PRD is modeled, which allows PJM to override the response characteristics based on historical performance data. PRD differs from traditional demand response in that PRD loads cannot be dispatched by operators directly. Instead, PRD loads are expected to respond following the demand response price curve.

C. PRD Response Dead-band

A PRD controller could set a dead-band to avoid frequent changes to the activation and deactivation statuses of the load due to price spikes. The PRD model simulates this control logic in order to anticipate actual response of PRD loads. A PRD load shall only be activated when the LMPs continue exceeding the lower band price for a period longer than a specific time limit, i.e. activation dead-band time. For the same reason, when a PRD load is activated, only when the LMP is lower than the lowest band price for longer than a specific time limit, i.e. deactivation dead-band time, will it be deactivated. Otherwise, it shall remain at the activation status.

IV. PRD MODELLING IN SCED ENGINE

A. PRD Model

1) PRD Response Range

For a PRD load at interval *t*, a constraint will enforce that the load MW will be within the range:

$$PRDMin(t, prd) <= PRDMW(t, prd) <= PRDMax(t, prd) \quad (1)$$

2) PRD Response Model

For each band of PRD response curve, there will be a band specific load MW, *PRDBandMW(t,prd,band)*, which should be within the range of [0, *BandWidth(t,prd,band)*].
A PRD load MW should be the summation of the band load MW. That is:

$$PRDMW(t,prd) = sum(band, PRDBandMW(t,prd,band)) \quad (2)$$

For block-loaded PRD loads, the load MW depends on the band width of the price curves. The below constraint is formulated for the block-loading logic:

$$PRDBandMW(t,prd,band) = iLoadedBand(t,prd,band) * BandWidth(t,prd,band) \quad (3)$$

Where :

iLoadedBand indicates whether a load band is activated or not.

For the smooth-loading feature, the constraint is:

$$PRDBandMW(t,prd,band) <= iLoadedBand(t,prd,band) * BandWidth(t,prd,band) \quad (4)$$

3) Dead-band Model

Currently, a primal model is used in SCED engine, where dispatch MW are decision variables in RT SCED. Since LMPs won't be available until the dispatch solution is obtained, it's impossible to determine the activation /deactivation status of PRD loads based on LMP values directly with the existing model.
To handle this, a two-solve based approach is used:

- In the first solve, based on the LMP calculated, activation/deactivation of PRDs will be derived heuristically according to the dead-band logic.
- Based on the activation/deactivation status of PRDs, resolve the complete model with the PRD for the precise MW value of PRD loads. That is, the heuristic logic only determines PRD activation/deactivation status, PRD actual load MW after response is still calculated by the optimization engine.

B. Load Forecast Model

The "unrestricted" load forecast value, i.e., the original load before PRD response is considered in the model.

C. Power Balance Constraint Model

The existing power balance constraint is:

$$Sum(resource, DispatchMW(t,resource)) + TransactionMW(t) = Load(t) + Loss(t) \quad (7)$$

With the PRD model, the constraint shall be reformulated as:

$$Sum(resource, DispatchMW(t,resource)) + TransactionMW(t) = Load(t) + sum(prd, PRDMW(t,prd)) + Loss(t) \quad (8)$$

Here Load(t) is a system level load forecast value of all non-PRD loads.

D. Transmission Constraint Model

Currently, transmission constraint is modeled as:

$$Sum(dispatchMw\ (t,resource)*Dfax(t,resource)) + Constant\ term1(t) <= flowLimit\ (t) \quad (9)$$

Where the constant term 1 includes impacts of fixed load, fixed transactions, and bias caused by DC model vs. AC model and the linearization for resource sensitivity calculation.

With the integration of PRD, the formulation shall include the PRD term, that is:

$$Sum(resource,DispatchMW\ (t,resource)*Dfax(t,resource)) + sum(prd,\ PRDMW(t,prd)*Dfax(t,prd)) + Constant\ term\ 2(t) <= flowLimit\ (t) \quad (10)$$

Here different from constant term 1, in constant term 2, only non-PRD loads are include as the fixed load.

E. Objective Function Formulation

In addition to existing resource operation costs and constraint violation penalty related terms, there will be a PRD related term. Formulation of the objective costs is changed to:

$$Existing\ objective\ costs - Sum((t,prd,band),\ PRDBandmw(t,prd,band)*BandPrice(t,prd,band)) \quad (11)$$

V. Case Studies

To evaluate the impact of PRD, a large number of studies have been conducted on PJM RT production cases. With the peak load of about 137GW, a PJM full-sized production case usually includes around 14,000 buses, 19,000 branches and 1,100 generators. It's assumed that 5% of load nodes are PRD loads, which are about 500 PRD loads. The demand response curves are fabricated, which usually have ten bands with equal band widths. Among all PRD demand response curves, the lowest strike price varies between 95 $/Mwh and 105 $/Mwh. The highest band price range is between 520 $/Mwh and 580 $/Mwh. For dead-band logic, activation dead-band time and deactivation dead-band time are both set as 15 minutes.Based on comparison between the solutions without and with PRD, PRD's impact on various aspects of market operation in RT time frame have been evaluated thoroughly, including:

A. SMP/LMP

System marginal price (SMP) profiles with and without PRD model are shown in below figures, where Fig. 2 is for the SMP and Fig. 3 is the LMP for an individual bus. It's seen clearly that the response of PRD can reduce the SMP or LMP by avoiding dispatch of expensive resources. The demand elasticity brought about by the PRD helps mitigate price volatility.

The PRD affects MCP by reducing load in response to high LMPs. With a lower SMP and alleviated congestion status, the overall LMPs are reduced. Taking bus BAYONNE 138KV 13KV-4, as an example, where there is a PRD connected, the LMP profiles are depicted in Fig. 3. It's observed that with the response of PRD to high prices, the LMPs are lower than the original values. It's also seen that the PRD helps to smooth out price profiles.

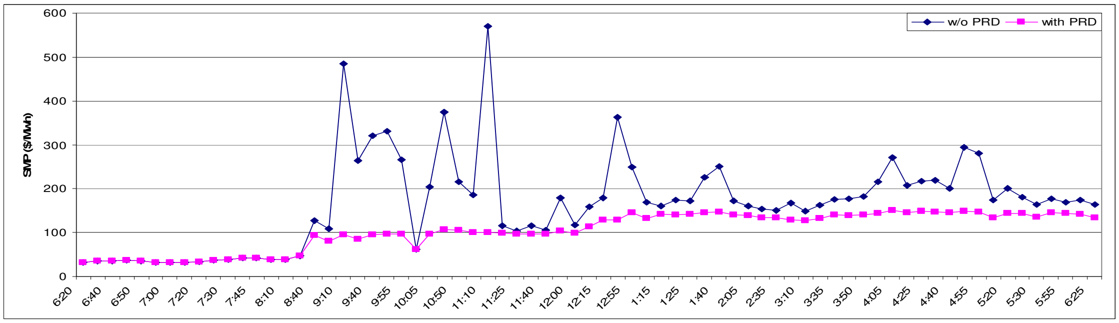

Fig. 2 SMP profiles without PRD and with PRD

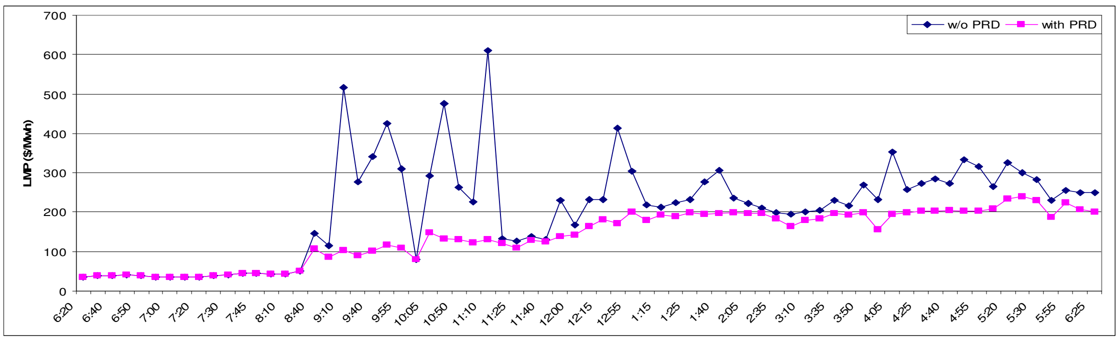

Fig. 3 LMP profiles of pnode BAYONNE 138KV 13KV-4 without PRD and with PRD

For some buses, LMPs are higher with PRD response. This is caused by the relative location of the bus with respect to active transmission constraints. Taking bus HARR APS20KV GEN3 as an example, in some intervals, the LMPs are higher than the original values because of the effects of binding constraints, as shown in Fig. 4. There is a generator connected to this bus. At interval 10:30 am, the bus has a 47 percent "lower helps" distribution factor on a binding constraint. Without PRD, this constraint's marginal price is -$400 /Mwh, thus the congestion contribution to the LMP is -$188 /Mwh. With the response of PRD, the constraint is not binding any more, i.e., the congestion contribution is 0. As a result, the LMP with PRD is greater than the original value.

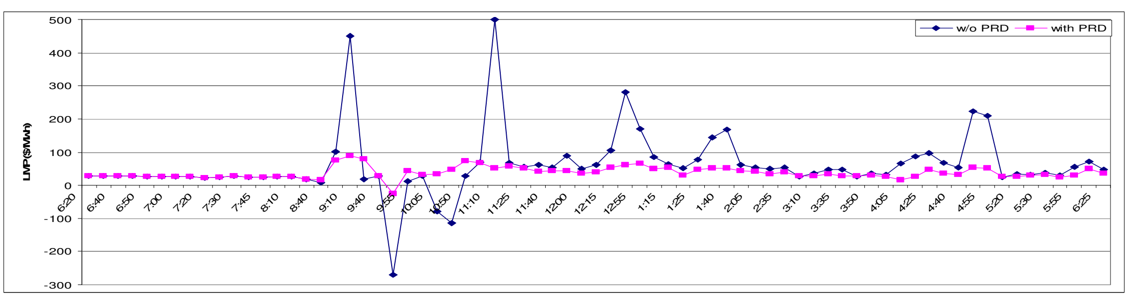

Fig. 4 LMP profiles of Pnode HARR APS20KV GEN3 without PRD and with PRD

B. AS market clearing price

The PRD load reduction frees up more generating resource capacity, which are available for AS procurement. Therefore, AS MCPs are lower in the solutions with PRD. Regulation MCP profiles without PRD and with PRD are shown in Fig. 5. At some intervals, such as 1:45 pm and 3:15 pm, the system was originally in a scarcity condition with a high price for frequency regulation. It's seen that the PRD helps mitigate the situation.

It's also seen that for a few intervals, such as 9:40 am and 11:30 am, the regulation MCPs with PRD are higher. The reason is, LMPs of some buses increase due to status changes in binding transmission constraints. The regulation MCP is set by the resource connected to one of the buses, therefore, higher lost opportunity costs (LOC) cause higher MCPs. The solution of higher regulation price with PRD at those intervals is valid.

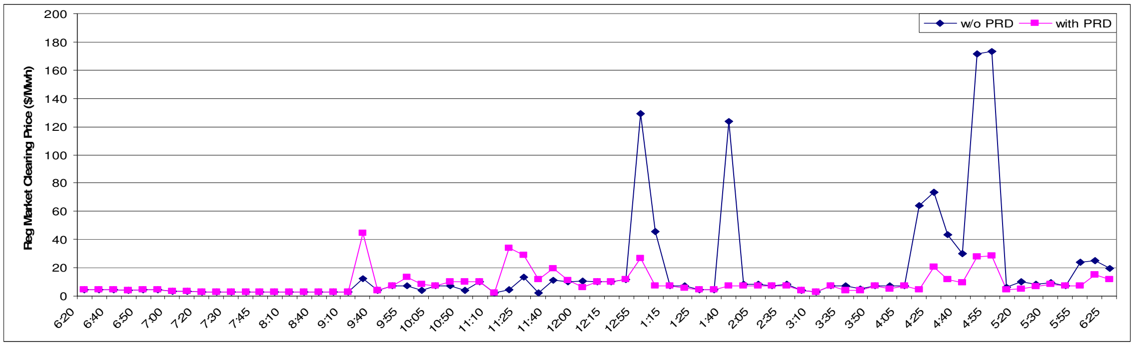

Fig. 5 Regulation MCP profiles without PRD and with PRD

The system spinning reserve MCP profiles are illustrated in Fig. 6. It's seen in the case without PRD model, spinning reserve is in scarcity situation in a few intervals around 5:00 pm, with prices at about $130/Mwh. With the response of PRD, the clearing price has been reduced significantly.

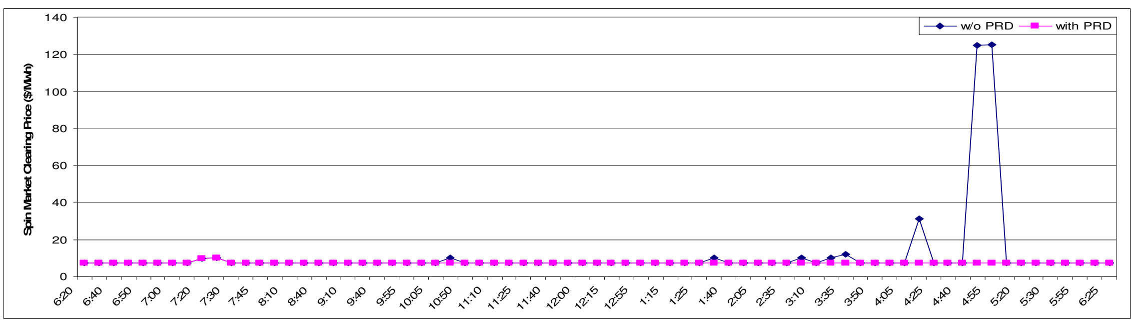

Fig. 6 System level spinning reserve price profiles without PRD and with PRD

C. Load curve

With the response of PRD to high LMPs, the peak load was reduced significantly. In Fig. 7, the load forecast profile is displayed against the actual load curve with PRD response. It's observed that with the response of PRD to the high LMPs, actual load is lower than the original load for the intervals. The original peak load was 135,830MW, with PRD response, it's reduced by 1.7 % to 133,538MW. With more PRD loads in the system, the peak shaving effect will be more significant.

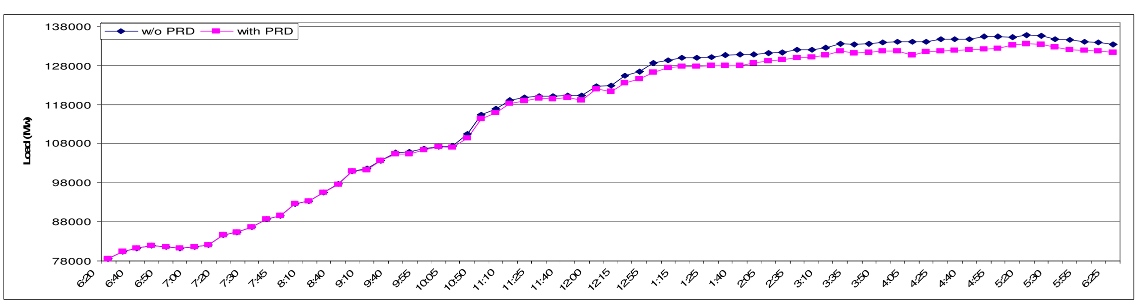

Fig. 7 System load profiles without PRD and with PRD

D. Resource dispatch

With the response of PRD, it's observed that relatively expensive resources are dispatched down due to load reduction. Taking unit AES_GC_1_21 CT as an example, the dispatch level changes are shown in Fig. 8. Its price varies between $59.06/Mwh to $63.87/Mwh. It is a relatively expensive unit and is dispatched down in most of the afternoon intervals with the response of PRD.

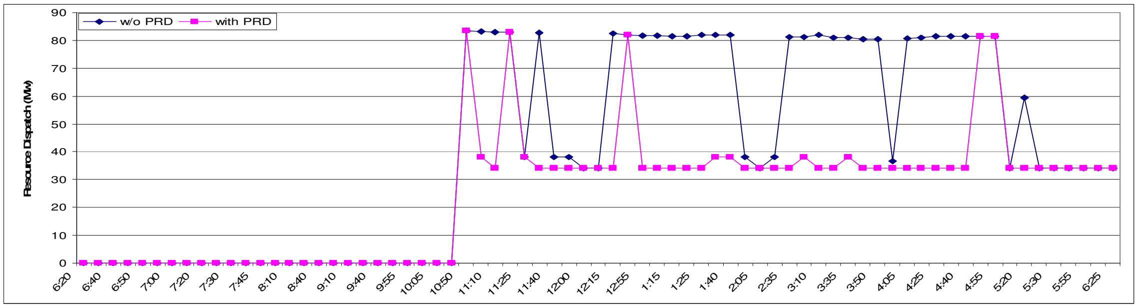

Fig. 8 Dispatch of unit AES_GC_1_21 CT without PRD and with PRD

E. *Changes in load payment due to PRD*

PRD response reduces load MW, as well as the LMP, it leads to load payment savings. As shown in Fig. 9, the total payment saving is $9570, which is 14.5% of the original load payment. This high payment saving percentage resulted from only 1.2% load reduction. Clearly, introducing demand elasticity through the implementation of PRD can provide a cost-efficient solution to energy consumers.

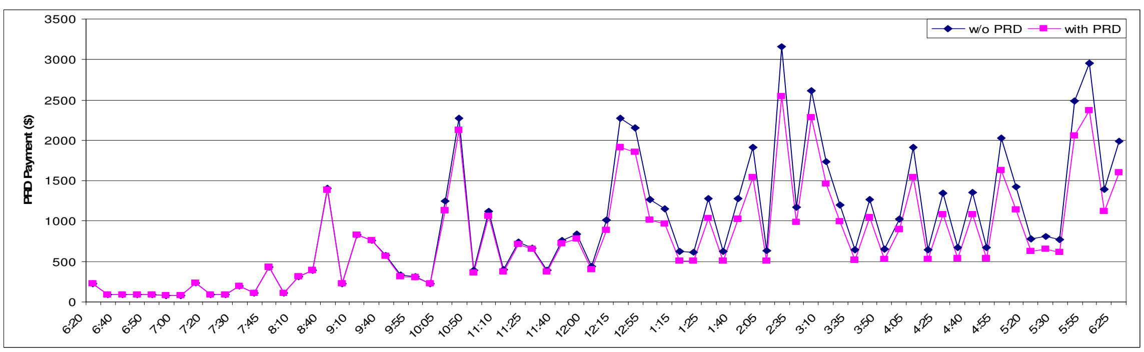

Fig. 9 Original load payment vs. load payment with PRD response

VI. CONCLUSIONS

As the next generation of demand response, PRD allows residential and small commercial consumers to voluntarily adjust their consumption according to dynamic retail price changes. From the perspective of RTOs/ISOs, high penetration of PRD will bring forth substantial benefits to system planning and market operations.

In this paper, the PRD model has been described. The PRD integrated RT market clearing engine can manage transmission constraints and dispatch resources by recognizing and leveraging consumer consumption patterns that respond to changing wholesale energy prices. Results from the studies provided strong evidence that the modeling of PRD in wholesale markets can reduce system production costs and better manage or altogether avoid emergency conditions.

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Ying Xiao received her BSEE from Hefei University of Technology, her MSEE from China Electrical Power Research Institute (CEPRI) and her Ph.D. from Brunel University, UK. She joined ALSTOM Grid in 2003 and has been working on designing and implementation of Market Management System (MMS). Currently, she is technical lead of PJM MMS team. Her interests include smart grid, risk management in power system operation. She is a senior member of IEEE.

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