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Implementation of Demand Response in Different Control Strategies of Smart Grids

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Abstract—**Smart grids facilitate the implementation of demand response programs by providing suitable communication infrastructure. The demand bidding/buyback is one of the demand response (DR) programs that encourages large consumers to change their energy consumption pattern and decline their peak load in return for financial rewards. In this paper, implementation of the demand bidding/buyback program in centralized and fully distributed control strategy is modeled, and the required information exchanges are depicted. Finally, features of each control strategy are summarized.**

Keywords-demand respons; smart grid; centralized control strategy; fully distributed control strategy.

I. INTRODUCTION

Smart grid refers to the operation of the power system using communication, power electronics, and storage technologies in order to balance supply and demand at all levels [1]-[3]. Two-way communication infrastructure used in smart grids facilitates effective participation of supply and demand side in electricity markets.

Demand response can be used as a tool to improve energy efficiency and reduce overall electricity consumption [4]. Demand response can be used to reduce power imbalances resulted due to penetration of renewable energies and other uncertainty resources. Demand bidding/buyback (DB) as a DR program is a procedure that encourages the large industrial consumers to decline their demand in hours needed and gain rewards in return. In the other words, this method is a tool for system operator to reduce costs and improve the security of the system [4]. Mostly, the participants of demand bidding/buyback programs are industrial large consumers who have the ability to change their consumption patterns [5]. In [6], an effective and simple model has been proposed for the demand bidding/buyback program in consumer's point of view.

According to the communication infrastructure used in smart grids, two distinct control strategies can be used in electricity markets: 1) centralized control strategy 2) fully-distributed control strategy [7]. These control strategies are different in information flow and settlement procedure. In this paper, the required information exchanges and optimization problems in order to settle market equilibrium in each mentioned control strategies are reported and the features of each control strategy are investigated.

The rest of this paper is organized as follows: the mathematical model of the DB program in consumer's point of view is involved in Section II. In Section III, two distinct control strategies used in smart grids are explained. Section IV is devoted to the implementation of demand response in different control strategies. Discussions and conclusions are reported in Sections V and VI, respectively.

II. MODEL OF DEMAND RESPONSE: DEMAND BIDDING/BUYBACK

Demand bidding/buyback (DB) is a demand response program that encourages industrial large consumers to reschedule their energy consumption and decline their load in peak hours in return for financial rewards. In this paper, DB is considered as a tool for system operator to operate the power system in a more efficient manner, reduce price spikes, and compensate energy unbalances results from intermittency of renewable energies.

In demand bidding/buyback program, consumers can directly incorporate in the electricity market by bidding for curtailing their purchased demand at the price that is determined by the system operator. Consumers' incentives to participate in DB are the two following benefits: reduce electricity consumption costs and increase profit by rescheduling the electricity consumption pattern. In [6], a simple and efficient model for DB in consumer's point of view is proposed. Since the large industrial consumers are the participants of DB program and their profit depend directly on their electricity consumption, they have little tendency to decrease their load. So, in this model, the load reduction periods are compensated in off-peak hours. The DB model is formulated as an optimization problem as follows [6]:

$$\underset{P_t^{d\prime}}{Max.} \sum_{t=1}^{N} \Delta \quad + \sum_{t=1}^{N} \sum_{\substack{k=1 \\ k \neq t}}^{N} \pi \quad \times \quad {}^{DB} \tag{1}$$

$$(\quad {}^{2} \quad 2 \quad {}^{\prime}) \quad \lambda$$

$$\Delta P_t^{d} = P_t^{d\prime} - P_t^{d} \quad ; \quad P_t^{DB} = -\Delta P_t^{d},$$

$$\sum_{t=1}^{N} P_t^{d\,\prime} = \alpha \times \sum_{t=1}^{N} P_t^{d} \tag{2}$$

$$P_t^{d\,\prime} \geq \eta_{1t} \times P_t^{d} \quad ; \quad 0 \leq \eta_{1t} \leq 1 \tag{3}$$

$$P_t^{d\prime} \leq (1+\eta_{2t}) \times P_t^{d} \quad ; \quad 0 \leq \eta_{2t} \leq \beta_t \tag{4}$$

$$\pi(t,t_c) = -\frac{P_t^{d\prime} - P_t^{d}}{\Delta P_{t_c}} \quad , \; t \neq t_c \tag{5}$$

$$\pi(t_c,t_c) = -1 \tag{6}$$

where:

g, h	Coefficient of consumer's revenue function
$P_t^{d\prime}$	Consumption at time t after load change in p.u
λ_t	Energy price at time t
N	Study period
t_c	Subset of N in which the demand reduction is recalled
α	Percent of load recovery
P_t^{DB}	Load reduction at the time of recall t in p.u.
B_t	Load curtailment price; has been determined by system operator in $
η_{1t}	Percent of load which defines the base load at time t
η_{2t}	Percent of load increase at time t
β_t	Permitted load increase at time t
$\pi(t,k)$	Component of load redistribution matrix (see [6])

Notice that, the profit of the consumer participating in demand bidding/buyback program is assumed as follows:

$$F(P) = (g \times P - h \times P^2) - \lambda \times P + \text{DR Rewards} \tag{7}$$

III. Control Strategies and Information Exchanges

In this section, two types of control strategies used in smart grids, and their information flow are reported [8].

A. Centeralized Control Strategy

In the centralized control strategy, control center gathers/sends information from/to system users, and all the simulations are done in this center. Figure 1 depicts the information exchange between system users and the system operator in centralized control strategy.

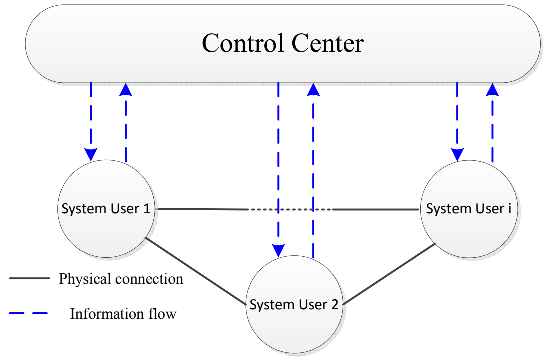

Figure 1. Information exchanges in centralized control strategy

B. Fully Distributed Control Strategy

In fully-distributed control strategy, each system user acts as a distributed control center and optimizes its own objective. In other words, the simulations are shared between system users and the feasibility of them is checked by a unit control center and required controlling signals are sent to the system users, accordingly. Figure 2 depicts the information exchange between system users and the system operator in fully distributed control strategy.

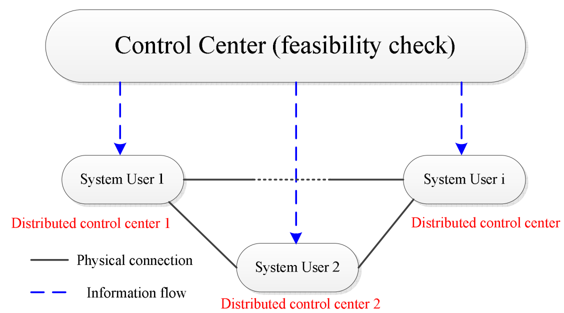

Figure 2. Information exchanges in fully-distributed control strategy

IV. Implementation of Demand Response in Smart Grid

In this section, dispatch of energy in electricity markets considering demand side participation is presented according to different control strategies reported in Section III. The information exchange required for implementation of the demand bidding/buyback program in electricity market, and the relevant optimizations are defined in each control strategy. Here, a security-constrained economic dispatch (SCED) is used that accounts for generators' ramping rates.

A. Centeralized SCED with DB Included

The system users in Fig. 1 are generation companies (GenCo) and industrial consumers (IndCo). The GenCo i must provide a supply function vector ($\overline{SF_i} = [SF_i^t(P_{Gi}), t \in N]$) as well as its ramping rate (R_i), and IndCo j runs the optimization problem (1) to (6) and bids for load curtailment ($\overline{P_j^{DB}} = [P_{j,t}^{DB}, t \in t_c]$).

The system operator implements the centralized SCED (equations (8) to (15)) and sends back the optimal dispatch quantities ($\overline{P_{Gi}}^{*} = [P_{Gi,t}^{*}, t \in N]$ and $\overline{P_j^{DB}}^{*} = [P_{j,t}^{DB*}, t \in t_c]$), market clearing prices ($\overline{\lambda_i} = [\lambda_{i,t}, t \in N]$) and load curtailment prices ($\overline{B_j} = [B_{j,t}, t \in t_c]$) to the system users. Figure 3 illustrates the information flow in centralized SCED.

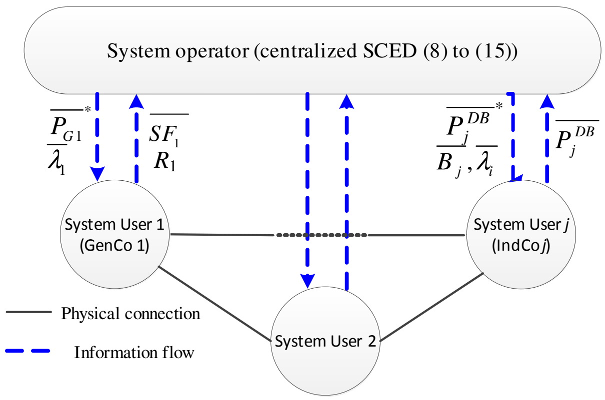

Figure 3. Information exchanges in centralized SCED with DB

The centralized SCED formulation supposing affine supply function for GenCos is included below. This model is a multi period economic dispatch considering ramping rates that is driven from the proposed model in [9].

$$\underset{P_{Git},P_{j,t}^{DB}}{Min.} \sum_{i=1}^{I}\sum_{t=1}^{N}(a_{i,t}+b_{i,t}P_{Git}^{g}+c_{i,t}{P_{Git}^{g}}^{2})+\sum_{j=1}^{J}\sum_{t\in 1}^{t_c}B_{j,t}P_{j,t}^{DB} \tag{8}$$

Subject to:

$$f_{k,t}(P_{Gk,t},P_{k,t}^{DB},\delta_{k,t}):\lambda_{k,t}\ ;\ k=1,\dots,n\ ,\ t=1,\dots,N \tag{9}$$

$$P_{Gi}^{g,\min} \le P_{Git}^{g} \le P_{Gi}^{g,\max} \quad t=1,\dots,N\ ,i=1,\dots,I \tag{10}$$

$$0 \le P_{j,t}^{DB} \le P_{j,t}^{DB,\max} \quad t\in t_c\ ,\ j=1,\dots,J \tag{11}$$

$$Q_t+\sum_{j=1}^{j=J}\Delta q_{tj}=\sum_{i=1}^{I}P_{Git}^{g} \quad t=1,\dots,N \tag{12}$$

$$P_{Git}^{g}-P_{Git-1}^{g}\le R_i\ ;\ t=1,\dots,N \tag{13}$$

where,

$$\Delta q_{tj}=\sum_{k=1}^{N}\pi_j(t,k)P_{j,k}^{DB}\quad ;\ j=1,\dots,J \tag{14}$$

$$\sum_{t\in t_c}P_{j,t}^{DB}\le Y_j\quad ;\ j=1,\dots,J \tag{15}$$

$a_{i,t}, b_{i,t}, c_{i,t}$	Supply function coefficients of generator *i* at time t
$B_{j,t}$	Load reduction price of consumer *j* at time *t*
$f_{k,t}$	DC load flow equation for bus *k* at time *t*
$\delta_{k,t}$	Voltage bus angle of bus *k* at time *t*
n	Number of buses
I	Number of participants in generation side
J	Number of participants in demand side
P_{Git}^{g}	Generation of generator *i* at time *t*
$P_{j,t}^{DB}$	The amount of load reduction of consumer *j* at time *t*
$P_{Gi}^{g,\min}$	Minimum generation limit of generator *i*
$P_{Gi}^{g,\max}$	Maximum generation limit of generator *i*
$P_{j,t}^{DB,\max}$	Maximum load reduction limit of consumer *j* at time ; that is equal to the load reduction bid of consumer j at time t
Q_t	Forecasted load at time *t*
Δq_{tj}	Demand change in case of load reduction recall
$\pi_j(t,k)$	Component of load redistribution matrix of consumer *j*
Y_j	The amount of reduced energy that the consumer *j* can decrease

B. *Fully Distributed Economic Dispatch with DB*

In fully distributed economic dispatch, each system user (GenCo and IndCo) must run its optimization problem based on the information that is given by the system operator ($\lambda_{i,t}$ and $B_{i,t}$). The system operator checks the feasibility of network in time step *t* by the equation of power generation and demand imbalance and posts new prices for energy and load curtailment to give incentives to system users to balance the system. In generation side, control on generation can be done by appropriate price signals for energy and in demand side, controlling process is don bye adjustment of load curtailment prices as well as energy price signals.

Accordingly, the fully distributed economic dispatch is an iterative process and the adjustment by the system operator must be done until equilibrium is reached [7]. Figure 4 illustrates the required information exchange to implement fully distributed economic dispatch.

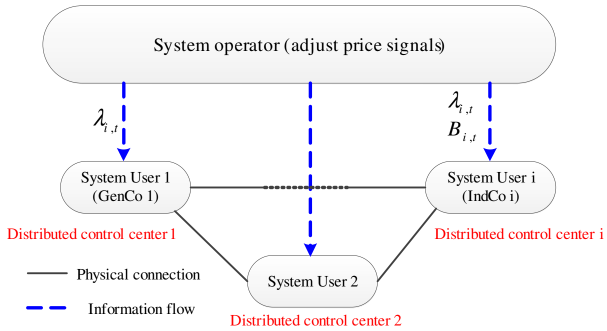

Figure 4. Information exchanges in fully distributed economic dispatch

V. Results and Discussions

In this paper, incorporation of demand response in two different control strategies, centralized dispatch and fully distributed dispatch, is investigated. Demand bidding /buyback program as a demand response program is considered in the models. The features of the two different control strategies are summarized below:

- In the centralized dispatch, the system operator provides energy and load reduction prices and optimal dispatched values of generation and load reduction obtained from previous market horizon for system users. According to the information and price forecast, a Genco provides its supply functions as well as its ramp rate and an IndCo bids for load reductions for the next market horizon. The system operator collects the information and runs a centralized economic dispatch for the future market horizon.
- The centralized SCED wit DB included problem is a quadratic programming and its complexity increases due to increase in system users.
- The centralized SCED requires two-way communication infrastructure.
- In the fully distributed economic dispatch with DB, each system user runs its own optimization problem with regarding to the price signals of energy and load reduction provided by the system operator. The system operator updates price signals according to energy imbalances.
- In fully distributed strategy, the system users are not required to communicate anything back to the system operator. So, one-way communication infrastructure is enough for this control strategy.
- The fully distributed economic dispatch always leads to small imbalances between supply and demand due to distributed decision-making process. Such imbalances lead to frequency deviations.
- Incorporation of demand response in fully distributed economic dispatch enables the system operator to reduce the mentioned frequency deviations by additional controlling signal that is the load reduction price. However, more study should be done to make this algorithm implementable.
- The advantages of the fully distributed dispatch strategy are: 1) reduced complexity of settling market equilibrium for the system operator 2) one-way communication system requirements. And its disadvantage is the inevitable small imbalances between supply and demand resulted from using this strategy.

VI. Conclussions

In this paper, participation of demand response in energy markets in two different control strategies used in smart grids has been investigated. Demand bidding/buyback has been considered in the model, and its implementation has been investigated in centralized and fully distributed control strategies.

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