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Reward/Penalty Design in Demand Response for Mitigating Overgeneration Considering the Benefits from both Manufacturers and Utility Company

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Abstract

The high penetration of renewable sources in electricity grid has led to significant economic, environmental, and societal benefits. However, one major side effect, overgeneration, due to the uncontrollable property of renewable sources has also emerged, which becomes one of the major challenges that impedes the further large-scale adoption of renewable technology. Electricity demand response is an effective tool that can balance the supply and demand of the electricity throughout the grid. In this paper, we focus on the design of reward/penalty mechanism for the demand response programs aiming to mitigate the overgeneration. The benefits for both manufacturers and utility companies are formulated as the function of reward and penalty. The formulation is solved using particle swarm optimization so that the benefit from both supply side can be maximized under the constraint the benefit of customer side is not sacrificed. A numerical case study is used to verify the effectiveness of the proposed method.

Peer-review under responsibility of the scientific committee of the Complex Adaptive Systems Conference with Theme: Engineering Cyber Physical Systems.

Keywords: Renewable Sources; Overgeneration; Reward/Penalty; Demand Response.

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1. Introduction

Electricity is the main energy input for many manufacturing systems. It is considered one of the world's fastest-growing form of end-use energy consumption [1]. By International Energy Outlook 2016 Reference case, world net electricity generation will increase 69% by 2040, from 21.6 trillion kilowatt-hours (kWh) in 2012 to 25.8 trillion kWh in 2020 and 36.5 trillion kWh in 2040. It can be expected that the Greenhouse Gas (GHG) emission will also witness a significant increase if all the increase portion of electricity generation is from traditional fossil fuel sources.

To address such a concern of GHG emission in future decades, the use of renewable sources, e.g., wind and solar, to generate electricity is of high interests of government, industry, and academia. It is considered one of the promising alternatives that can meet the energy challenge of 21st century to create a truly sustainable energy ecosystem for the planet. Although fossil fuel is still the main source of electricity generation, the generation mix has been changed significantly over the past several decades. The energy generated from the renewable sources accounts for about 13.4 percent of nation's total electricity production [2].

Solar cells, also called photovoltaic (PV) cells, currently represent the fastest growing renewable energy technology, making them a major player in the mix of global electricity generation. With steady improvements in new materials, and scaled up manufacturing, solar energy technologies are more affordable than ever. All these benefits accelerate the growth of the adoption of solar energy system. However, due to uncontrollable property of renewable sources, it creates sudden imbalance between high supply and low demand during overgeneration period during which the solar energy ramps so fast that the generation is higher than the demand. This asynchronous generation in terms of demand limits operational flexibility and degrades the reliability of the grid. Thus, further integration of large scale renewable sources becomes a challenge with respect to cost effectiveness and grid reliability.

Curtailment of renewable energy supply during overgeneration period can be a straightforward measure to deal with overgeneration. It can relieve imbalance situation and improve the reliability. There has been a great deal of research focusing on renewable energy supply curtailment strategies for different types of renewable resources. For example, Viganò et al. analyzed the active power supply curtailment strategies for renewable distributed generation [3]. Luhmann et al. illustrated the approach of excessive supply curtailment of distributed renewable energy for cost-efficient grid integration [4]. Tonkoski et al. showed the effective way of coordinated active power supply curtailment of grid using PV inverters for overvoltage prevention [5]. Kane L. and Ault G. reviewed renewable energy supply curtailment schemes in transition towards business [6].

However, the curtailment of excessive supply sacrifices the benefits of the stakeholders and weakens their confidence for further investment. Some analysis shows that if the curtailment is around 5 percent—owners of renewable projects face a significant risk of not being able to pay off loans for existing projects or secure financing for new projects [7].

Another measure to handle overgeneration is to incur more energy demand to fully utilize of the over generated electricity from the renewable sources. Some existing research focusing on this management technique has been reported. For instance, Rad et al. developed the autonomous demand-side management technique based on game-theoretic energy consumption scheduling for the future smart grid [8]. Yan et al. developed demand response support under weather impacts of renewable sources. They both integrated the PV generation and electric vehicle energy storage to mitigate the negative impact [9]. Nguyen and Le introduced optimal energy trading strategy for building microgrid with electric vehicles and renewable energy resources [10].

These demand side management programs can be helpful to address the overgeneration problem without any curtailment of renewable energy. To implement these programs successfully, the demand behavior of the manufacturers, a major customer group who contributes around 1/3 of total energy consumption around the U.S. [11], needs to be adjustable according to the overgeneration profile of the renewable sources. However, there needs some driving force that can encourage them to shift their load. Therefore, developing an optimal incentive strategy to encourage the manufacturers to participate in the program is the motivation of the paper.

In this paper, we focus on the design of reward/penalty mechanism for the demand response program aiming to encourage the manufacturers to participate in the program dealing with overgeneration to enhance the grid performance in a cost-effective and safe manner. A certain number of manufacturing customers will be selected at each time interval during overgeneration periods to provide the additional energy consumption to mitigate overgeneration so that the benefits of the utility company can be maximized. Different parameters such as the over generated electricity at the interval, the value created by each manufacturer consuming unit electricity, the consumption capability of each manufacturer, the rate of reward & penalty at each interval, and unit selling price of electricity are modeled in the objective function and constraints. Particle Swarm Optimization (PSO) is used to find a near optimal solution of the penalty and reward mechanism. The rest of this paper is organized as follows. The proposed modeling method including both problem formulation and solution technique is introduced in section 2. A numerical case study is illustrated in section 3. Finally, conclusions is drawn and future work is discussed in Section 4.

2. Proposed model

2.1. Problem formulation

In demand response program to mitigate overgeneration, utility company will announce the desired additional electricity consumption at each period throughout the overgeneration period for different manufacturers. If the manufacturer can additionally consume this desired amount of energy at the given period, the bonus will be paid based on a given reward rate. The designed reward rate can encourage the manufacturers to utilize the over-generated electricity. If not, the penalty will be charged based on the specific penalty rate, which restrict them to consume the committed electricity. Therefore, grid stability can be improved.

Consider that there are *N* manufacturers who can be the potential participators to the demand response program to mitigate overgeneration. Let i =1, 2, ..., N be the index of each manufacturer. The time horizon of overgeneration period is known and divided into a set of intervals. Let, t =1, 2, …, T be the index of each interval. Let $q_i(t)$, $r_i(t)$, and $f_i(t)$ be the announced desired additional consumption from manufacturer i at time period t, the reward that manufacturer i will receive if they can achieve the desired additional consumption at period t, and the penalty that manufacturer i needs to pay if they cannot achieve the desired additional consumption at period t, respectively. In this model, we will identify the optimal $q_i(t)$, $r_i(t)$, and $f_i(t)$ so that the benefits of the utility company can be maximized.

Let $P_i(t)$ be the probability that manufacturer i can obtain the rewards offered by the utilities companies by participating in the program at period t. We model this probability as the function of the value created by consuming unit electricity, the rate of reward & penalty, and the electricity consumption cost as shown in (1). $v_i(t)$ is the value that can be created by manufacturer i when consuming unit electricity at period t. c_s is the unit electricity purchase price. Δr and Δf are the unit variation of reward rate and penalty rate, respectively.

$$P_i(t) = \frac{r_i(t)}{2(r_i(t) + \Delta r \times (\frac{c_s}{v_i(t)}))} + \frac{f_i(t)}{2(f_i(t) + \Delta f \times (\frac{c_s}{v_i(t)}))} \tag{1}$$

The increase of $r_i(t)$ will encourage the manufacturers to participate in the program and $f_i(t)$ will promote them to meet the required additional consumption. The valuation will also increase the probability to participate in the program, while per unit cost of electricity will decrease such a probability. Δr and Δf are used to make the units of the two terms in the denominators of (1) consistent. The value of Δr and Δf are selected in such a way so that the probability calculated is not dominated by the selected values. Note that if the selected values of Δr and Δf are much larger than the values of $r_i(t)$, $v_i(t)$, and c_s , the variation of the probability is mainly determined by Δr and Δf .

Let Q be the total expected electricity consumption throughout the overgeneration period, which can be formulated by (2).

$$Q = \sum_{t=1}^{T}\sum_{i=1}^{N} q_i(t) \times P_i(t) \tag{2}$$

Let I be the revenue due to selling the electricity, which can be formulated by (3).

$$I = c_s Q \tag{3}$$

Let P and R be the expected penalty and reward that utility company will receive and pay, respectively. They can be formulated by (4) and (5), respectively.

$$P = \sum_{t=1}^{T}\sum_{i=1}^{N} f_i(t) \times (1 - P_i(t)) \tag{4}$$

$$R = \sum_{t=1}^{T}\sum_{i=1}^{N} r_i(t) \times P_i(t) \tag{5}$$

Let $g(t)$ be the over-generated electricity needs to be consumed by the manufacturers at period t, and c_g be the unit generation cost. Let C be the total cost of over-generated electricity, which can be formulated by (6).

$$C = c_g \sum_{t=1}^{T} g(t) \tag{6}$$

The objective function can be formulated as

$$\max_{q_i(t)\, r_i(t)\, f_i(t)} I + P - R - C \tag{7}$$

The constraints can be formulated as follows. Grid stability constraint is used to describe that the gap between the electricity over-generated and expected consumption should be controlled below a certain level, which can be formulated by (8).

$$g(t) - \sum_{i=1}^{N} q_i(t) \times P_i(t) \le \varepsilon \cdot g(t) \tag{8}$$

where ε is maximum allowed gap percentage between the energy generated and consumed by customers.

The expected benefits of manufacturer when they participate in such demand response programs needs to be no less than zero, which can be formulated by (9).

$$\sum_{t=1}^{T} v_i(t) \times q_i(t) \times P_i(t) + r_i(t) \times P_i(t) - f_i(t) \times (1 - P_i(t)) - c_s \times q_i(t) \times P_i(t) \ge 0 \tag{9}$$

In (9), the first term is the expected value that can be created by achieving the required additional energy consumption. The second and third terms are the expected reward and penalty, respectively. The last term is the expected billing cost when purchasing such additional amount of energy from utility.

The benefits of utility company need to be larger than zero, which can be formulated by:

$$I + P - R - C > 0 \tag{10}$$

The desired additional energy consumption by manufacturer i at period t cannot be larger than the maximum additional energy can be consumed by manufacturer i at the time period t, $D_i(t)$, which can be formulated by (11).

$$q_i(t) \le D_i(t) \tag{11}$$

The sum of the desired additional energy consumption should be no higher than the over-generated energy for each period t.

$$\sum_{n=1}^{N} q_i(t) \le g(t) \tag{12}$$

2.2. Solution technique

Particle swarm optimization is used to solve this high-dimension optimization problem. The candidate solution is represented as a particle in a swarm. It is encoded into an ($3N\times T$) matrix. The ($3i$-2)th rows, i =1, …,N of the matrix is used to store the decision variable of $r_i(t)$, The ($3i$-1)th rows, i =1, …, N, of the matrix is used to store $f_i(t)$. The ($3i$)th rows, i =1, …, N, of the matrix is used to store $q_i(t)$. $r_i(t)$ and $f_i(t)$ are initialized by randomly selecting values between 1 and 10. $q_i(t)$ is initialized by randomly selecting values between 0 to 50.

The particles can fly in the search space based on the updated velocity towards its best location over time. After each flying step (or iteration), the velocity and location of each particle are updated according to (13):

$$V(s+1) = \alpha V(s) + c_1 w_1 (L_{PB} - L(s)) + c_2 w_2 (L_{GB} - L(s))$$
$$L(s+1) = L(s) + V(s+1) \tag{13}$$

where $V(s)$ and $V(s+1)$ are the velocity matrix of individual particle at iteration s and s+1 , respectively; $L(s)$ and $L(s+1)$ are the location matrix of individual particle at iteration s and s+1, respectively. Also, c_1 and c_2 are the learning factors and w_1 and w_2 are the random real numbers between zero and one. α is the inertia weight. To ensure better exploration and exploitation capability, α value is determined by the equation (14):

$$\alpha = \alpha_{\max} - \frac{\alpha_{\max} - \alpha_{\min}}{\mathrm{I}_{\max}} \times I \tag{14}$$

L_{PB} is the particle's best solution that has been identified up to the s th iteration. L_{GB} is the global best solution of the entire swarm.

Equation (15) is used to limit the scale of the velocity for updating reward/penalty rates between the interval [-2, 2]. Equation (16) is used to ensure that reward and penalty rates are non-negative.

$$V_{r_i(t),f_i(t)}(s+1) = \begin{cases} -2, & \text{if } V_{r_i(t),f_i(t)}(s+1) < -2 \\ 2, & \text{if } V_{r_i(t),f_i(t)}(s+1) > 2 \\ V_{r_i(t),f_i(t)}(s+1), & \textit{Otherwise} \end{cases} \tag{15}$$

$$L_{r_i(t),f_i(t)}(s+1) = \begin{cases} 0, & \text{if } L_{r_i(t),f_i(t)}(s) + V_{r_i(t),f_i(t)}(s+1) < 0 \\ L_{r_i(t),f_i(t)}(s) + V_{r_i(t),f_i(t)}(s+1), & \textit{otherwise} \end{cases} \tag{16}$$

$$L_{r_i(t),f_i(t)}(s+1) = 0, \quad \text{if } L_{q_i(t)}(s) + V_{q_i(t)}(s+1) = 0 \tag{17}$$

The equation (17) will ensure that if the required committed electricity consumption for manufacturer i at period t is assigned as zero, there will be no reward and penalty for the manufacturer at that period.

Similarly, equation (18) is used to limit the scale of velocity for updating $q_i(t)$ within the interval [-5, 5]. Equation (19) is used to ensure that $q_i(t)$ is non-negative. Equation (20) is used to assign the required committed electricity consumption as zero when the manufacturer has no possibility to obtain reward at that interval.

$$V_{q_i(t)}(s+1) = \begin{cases} -5, & \text{if } V_{q_i(t)}(s+1) < -5 \\ 5, & \text{if } V_{q_i(t)}(s+1) > 5 \\ V_{q_i(t)}(s+1), & \textit{Otherwise} \end{cases} \tag{18}$$

$$L_{q_i(t)}(s+1) = \begin{cases} 0, & \text{if } L_{q_i(t)}(s) + V_{q_i(t)}(s+1) \le 0 \\ L_{q_i(t)}(s) + V_{q_i(t)}(s+1), & \textit{otherwise} \end{cases} \tag{19}$$

$$L_{q_i(t)}(s+1) = 0, \quad \text{if } P_i(t) = 0 \tag{20}$$

The fitness function of an individual particle can be formulated as shown in (21) where the constraints (8) - (12) are integrated as penalty terms.

$$-(I+P-R-C)+A_1\sum_{t=1}^{N}\max(g(t)-\sum_{i=1}^{N}q_i(t)\times P_i(t)-\varepsilon\times g(t),0)^2$$
$$+A_2\sum_{i=1}^{N}\min((\sum_{t=1}^{T}v_i(t)\times q_i(t)\times P_i(t)+r_i(t)\times P_i(t)-f_i(t)\times(1-P_i(t))-c_s\times q_i(t)\times P_i(t)),0)^2 \quad (21)$$
$$+A_3\min(I+P-R-C,0)^2+A_4\sum_{i=1}^{N}\sum_{t=1}^{T}\max(q_i(t)-D_i(t),0)^2+A_5\sum_{t=1}^{T}\max(\sum_{i=1}^{N}q_i(t)-g(t),0)^2$$

where A_1, A_2, A_3, A_4, and A_5 are five large real numbers.

3. Case study

To illustrate the effectiveness of the proposed model, a numerical case study is implemented. In this case study, it is considered that twenty manufacturers are available in the market and the overgeneration period is between 9:00 AM to 1:00 PM . Every 15 minutes is considered a period. The over-generated electricity and per unit generation cost for each period are shown in Table 1. The values of Δr and Δf are set as \$3 through empirical testing with different values compared to the values of $r_i(t)$, $f_i(t)$, $v_i(t)$, and c_s.

Table 1. Over-generated electricity and per unit generation cost at each time interval

Period index	1	2	3	4	5	6	7	8
Time	9:00-9:15	9:15-9:30	9:30-9:45	9:45-10:00	10:00-10:15	10:15-10:30	10:30-10:45	10:45-11:00
$g(t)$ (kWh)	260	280	300	320	330	360	390	420
$c_g(t)$ (\$/kWh)	0.061	0.065	0.026	0.066	0.052	0.025	0.034	0.047
Period index	9	10	11	12	13	14	15	16
Time	11:00-11:15	11:15-11:30	11:30-11:45	11:45-12:00	12:00-12:15	12:15-12:30	12:30-12:45	12:45-1:00
$g(t)$ (kWh)	420	440	470	500	460	440	460	430
$c_g(t)$ (\$/kWh)	0.068	0.068	0.028	0.069	0.068	0.044	0.060	0.027

The maximum additional electricity (kWh) demanded by manufacturer *i* at first period, $D_i(1)$, is randomly selected between 10 and 30. Then, the quantity is continuously updated at next period by adding a variation to the previous demand quantity. The variation follows a normal distribution with mean of zero and standard deviation 10. Electricity selling price is considered constant throughout the overgeneration period and is set as 0.05/kWh. The renewable energy cost depends on different factors such as ramp rate, ramp time, start-up & shut down cost, maintenance cost, etc. In this paper, for simplicity, we find the renewable generation cost for each period *t* by randomly selecting the values from the range between 0.02/kWh to 0.07/kWh.

The value created by consuming unit energy by manufacturer *i* at period *t* is obtained by randomly selecting the values from the range between 0.03/kWh to 0.15/kWh. For grid stability, the electricity can fluctuate within a certain range of generation. In this case study, 14% electricity of total overgeneration is considered the tolerance at each period. PSO is encoded in Matlab and used to solve the proposed model. The learning factors c_1 and c_2 are set as 1.7 and 1.7, respectively. The maxima of inertia weight are set as 0.09 and minimum as 0.01. After tuning different PSO parameter combinations, we find that 8000 and 1000 is a reasonable parameter combination regarding swarm size and iteration number for PSO to balance solution quality and computational cost. The computational time to solve this case is 120129 seconds. The computer used is a desktop with an Intel(R) Core TM i5 CPU 650@ 3.20 GHZ processor, and a 4GB memory.

Table 2 shows the results of $q_i(t)$, and Table 3 shows corresponding results of $r_i(t)$ and $f_i(t)$. The over-generated energy and the total desired additional energy consumption of each period *t* are shown in Fig. 1.

Table 2. Required committed energy consumption for each manufacturer i at period t

Manufacturer i	Period t															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	22	18	21	22	0	26	12	24	0	29	12	27	31	23	24	16
2	15	18	0	0	17	27	17	28	26	17	0	19	15	28	26	20
3	0	15	20	13	17	0	24	30	30	15	27	25	30	27	27	27
4	0	15	29	13	21	13	17	13	16	0	12	29	28	26	28	25
5	17	0	0	0	12	11	17	23	22	30	30	35	30	18	13	26
6	19	18	0	18	28	21	12	13	22	29	20	27	11	11	24	30
7	15	0	14	0	16	0	29	20	18	12	18	12	12	25	29	20
8	0	22	19	26	28	20	0	16	19	20	28	35	31	28	26	23
9	23	24	13	17	0	29	13	22	22	22	24	31	15	20	0	24
10	13	12	30	17	0	25	12	12	23	28	28	28	22	22	30	13
11	12	23	22	0	28	23	13	30	16	14	22	17	28	13	20	13
12	13	0	0	20	19	29	28	25	17	16	25	28	27	11	29	15
13	13	18	22	12	20	0	26	14	11	19	21	35	25	28	26	29
14	20	15	21	30	0	24	25	0	21	12	18	0	13	12	22	0
15	15	0	21	12	19	27	22	19	22	26	30	22	12	29	17	25
16	20	25	0	11	0	0	13	21	19	26	27	21	30	30	29	26
17	0	27	19	11	28	13	17	26	15	25	13	27	0	20	27	15
18	15	12	0	16	30	15	13	30	30	29	23	25	30	28	15	19
19	21	0	13	23	0	21	17	25	19	20	30	27	23	24	29	21
20	0	17	22	19	11	15	20	16	28	30	17	20	30	0	15	25

Table 3. Reward and penalty rate offered for manufacturer i at period t

Manufacturers i	Interval t																															
	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16	
	r_1	f_1	r_2	f_2	r_3	f_3	r_4	f_4	r_5	f_5	r_6	f_6	r_7	f_7	r_8	f_8	r_9	f_9	r_{10}	f_{10}	r_{11}	f_{11}	r_{12}	f_{12}	r_{13}	f_{13}	r_{14}	f_{14}	r_{15}	f_{15}	r_{16}	f_{16}
1	3	8	6	1	4	5	7	9	0	0	10	8	10	3	9	8	0	0	5	4	4	1	3	2	2	7	8	1	7	3	6	8
2	8	9	8	3	0	0	0	0	4	5	9	4	4	3	10	1	8	10	8	6	0	0	6	6	7	6	2	3	10	10	8	4
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20	0	0	1	8	2	10	4	8	8	5	3	8	2	1	9	9	5	3	1	4	5	4	1	8	3	7	0	0	2	9	4	1

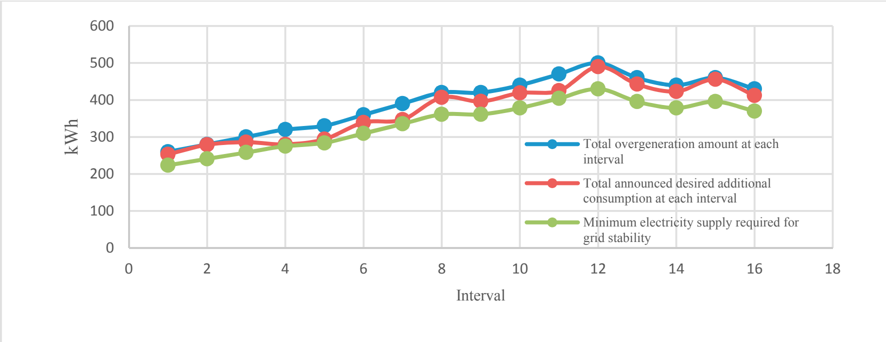

Fig. 1. Over-generated electricity and obtained power profile of required committed electricity at each interval.

The results of the case study show that the total announced desired consumption at each period satisfies the grid stability condition. It can facilitate utility company to implement such overgeneration mitigation oriented demand response programs. At the same time, the reward and penalty rates set for each manufacturer are identified in such a way so that each manufacturer is expected to make profit through this program. Thus, the manufacturers will be encouraged to participate the program.

4. Conclusion and Future Work

Renewable energy is a promising solution to address global climate change. However, the high penetration of renewable sources in the grid leads to overgeneration during specific periods when renewable energy source ramps up too fast. It impedes further adoption of renewable sources on a much larger scale. In this paper, we propose an optimization model to identify the critical parameters, i.e., the desired additional consumption, the reward rate, and the penalty rate, that are required in overgeneration mitigation oriented demand response programs. The interests from both utility company and manufacturing customers are considered. A numerical case study is used to illustrate the effectiveness of the proposed model.

For future work, the sensitivity analysis can be conducted to examine the influence of the variation of the input parameters on the final results to obtain deeper insights of this program. In addition, the feasibility and economic analysis of using energy storage system by utility companies to deal with overgeneration can also be studied.

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