Optimal control strategy of load aggregators with demand response

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Abstract: This study presents an optimal control strategy for a load aggregator (LA) with demand response. The LA can provide consumers with time-of-use electricity price which could be different with the selling price of electricity by power grid. At the same time, LA has some distributed photovoltaic power generations, several diesel generators and energy storage devices to ensure user reliability and improve benefits. The LA’s objective is to maximize its benefits without infringing the interests of consumers. A model of quadratical constraint quadratic programming is established to describe the above issues, and the generator-battery control strategy with demand response (DR) under optimal economic operation of the system is solved by CPLEX. The results show that the proposed management strategy and DR strategy improves the operational economy of the system.

1 Introduction

In recent years, the distributed energy resources and demand response have witnessed rapid development. On the one hand, their development can ease the shortage of electricity and reduce the environmental pollution caused by the power industry. However, on the other hand, disordered access to a large number of distributed generation will bring challenges to the control and stability of the power grid. At the same time, the small scale and scattered distribution of civil loads and the direct participation in the demand response of the power system will greatly increase the uncertainty of power system. Against this backdrop, the existence of load aggregators (LAs) has become one of the solutions to the above problems, and has received a lot of attention and research [1, 2].

LA is a power load intermediary where we define it as a company that acts as an intermediary between power end users that provide demand response resources and power system participants who want to buy those resources, enabling users access the electricity market in an effective way and provide more flexible services and technologies. It not only deals with power grids, but also provides customers with electricity sales services independently. The existence of LAs enhances the grid’s ability to manage loads and users’ demand responsiveness, and can reduce the operating costs of grid companies and users’ electricity costs, while also making profits for themselves.

From a system operator’s point of view, LA is a large power generator (similar to a virtual power plant) or load resource [3], which could provide schedulable generation capacity or ancillary services [4]. From the consumers’ perspective, LAs can provide them with a better demand response environment and reduce their electricity costs.

2 Methodology

The LAs studied in this paper are mainly serve for regional load of residential areas, and have a certain capacity of energy storage devices, distributed photovoltaic and diesel generators.

The whole system frame is shown in Fig. 1, in which the arrowed solid lines mean the power flow, and the arrowed dotted lines mean price information. It is obvious that electricity can flow in both directions between the LA and the power grid. By changing the electricity selling prices, the power grid can control the demand side response of LAs, and LAs change their operation management strategy to achieve the maximum benefit according to electricity selling price.

Fig. 2 shows predict time-sharing electricity load curve of a certain area in a working days to and the electricity selling prices. It can be seen that the time-sharing electricity price based on the operation characteristics of power grid are not completely consistent to the load characteristic of this region, which is because the area is mainly composed of residents load. So the electricity selling prices established by aggregators should not copy the peak valley of users’ load, or aimed at peak user load cutting settings, but should overall consider the grid electricity price, user needs, and aggregators power itself, the reasonable design of energy storage device. In this paper, the energy management strategy and user price setting mechanism model are put forward, and the method is solved by planning method.

Objective function:

\[
\max F_b = F_{b1} + F_{b2} - F_{c1} - F_{c2} - F_{c3}
\]

(1)

\[
F_{b1} = \sum_{i=1}^{24} (p_{pv,i} + p_{de,i} + p_{net,i} - p_{peak}) \cdot P_{c,i}
\]

(2)


The definition of the user's cross-elasticity represents the user's multi-period response:

$$
e_{ij} = \frac{(\Delta Q_i/Q_i)}{(\Delta P_i/P_i)}$$

(8)

According to the formulae (7) and (8), the electricity price elasticity matrix can be calculated as follows:

$$
E = \begin{bmatrix}
  \epsilon_{11} & \epsilon_{12} & \cdots & \epsilon_{1n} \\
  \epsilon_{21} & \epsilon_{22} & \cdots & \epsilon_{2n} \\
  \vdots & \vdots & \ddots & \vdots \\
  \epsilon_{m1} & \epsilon_{m2} & \cdots & \epsilon_{mn}
\end{bmatrix}
$$

(9)

The demand change from price change can be forecasted by elastic coefficient matrix as shown in (9).

### Constraints:

1) **Power limits:**

$$Q_{c,t} = Q_{c,t-1} + Q_{PV,t} + Q_{DR,t} \quad \forall t$$

(10)

The LA must meet the power demand of consumers at least.

2) **Diesel generation limits:**

$$0 \leq P_{d,e,t} \leq P_{de}^{max} \quad \forall i, t$$

(11)

The unit's output must be between the maximum output value and the minimum output value.

Equation (11) indicates that a unit can only carry out an operation in a period: start-up or shut down. Equation (9) states the change logic of units. Start-up means the action of setting in operation, which should change from none output to output and vice versa.

3) **Wind generation limits:**

$$0 \leq P_{PV,t} \leq P_{PV}^{max} \quad \forall i, t$$

(12)

The capacity of wind power output cannot exceed the maximum predicted value.

4) **DR limits:**

$$\sum_{i=1}^{T} Q_{c,i} \cdot P_{c,i} \leq \sum_{i=1}^{T} Q_{c,i} \cdot P_{G,t}$$

(13)

The user's electricity tariff under LA should not be higher than the electricity tariff under the grid price.

### 3 Results analyse

Under the grid TOU price (grid price), the parameters of a LA equipped with distributed PV, diesel generators (DE) and battery energy storage (BES) system are shown in Table 1. The photovoltaic output and grid power price forecast are shown in Fig. 3. According to China's current distributed photovoltaic subsidy standard, all photovoltaic power generation enjoys subsidies and can be sell to power grid according to the electricity price.

According to the model and costs calculation method proposed above, the management plan of LA is a quadratical constraint quadratic programming. We built the above model in MATLAB and solved by CPLEX.

Fig. 4 shows the load change under price-based demand response (histogram) and the TOU price (solid line) provided by

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**Fig. 2 Load curve and grid's electricity price**

**Table 1 Technical and economic data of generation units**

| Capacity (PV) | BES (kW) | DE (kW) |
|--------------|----------|---------|
| PV (after D) | PV (kW) | DE (kW) |
| PV (kW)     | 1500     | 200     |
| PV (kW)     | 150      | 20      |
| PV (kW)     | 0.30     | 0.10    |
| PV (kW)     | 0.85     | 0.02    |
| PV (kW)     | 0.15     | 0.6     |

The DR in the electricity market can be divided into the following two types according to the user's different responses: DR based on price (price-based DR) and DR based on incentive (incentive-based DR). In this model, the LA adopts the time-of-use (TOU) pricing policy which is one kind of price-based DR.

We built a demand response model based on the electricity price elasticity matrix [6]:

Define the user's self-elastic coefficient to represent the user's single time response:

$$\epsilon_i = \frac{(\Delta Q_i/Q_i)}{(\Delta P_i/P_i)}$$

(7)
LA. Fig. 5 shows the power energy exchange (histogram) between LA and the grid, and the grid power price (dotted line).

The TOU price provided by LA is completely different with TOU price of power grid, at some point, LA provides valley price while the grid is peak price, on the contrary, LA provides peak price while the grid is valley price. This is because the PVs owned by LA are in a state of high power generation when the grid is peak price. After a certain period of time after get-off work, the photovoltaic power generation is suspended because there is no light and the users have returned to their homes and caused the peak of electricity consumption as shown in Fig. 5.

Fig. 6 shows the optimal power management scheme for LA. It can be seen that during the grid peak price, BES, diesel generators and photovoltaic power generation emit as much energy as possible. At the grid valley price, the energy storage device is slowly charged to recover state of charge. Table 2 shows the list of benefits and costs of LA, after optimisation, the benefits obtained by LA and consumers are shown in Table 3. The result shows that under the proposed model and optimisation, LA can get benefit without infringing the interests of consumers.

4 Conclusion
LA participating in the power system operation can provide market regulator opportunities for demand response resources such as simply adjustable loads, energy storage devices and distributed power supplies. It can also fully develop load resources through professional technical and provide auxiliary service products for the markets. Residents load with photovoltaic and energy storage equipment has a greater demand response potential, but the response strategy involves multi-subjects and multi-dimensions of decision-making control. In this paper, we construct a reasonable decision model of LA including photovoltaic and energy storage, analyse the composition of costs and benefits, and discuss the impact of multivariate incentive mechanism on the decision-making of photovoltaic and energy storage capacity of load system. The result shows that:

(i) when the LA is equipped with photovoltaic and energy storage devices, the benefit of demand response is improved.
(ii) the time-sharing electricity price based on the operation characteristics of power grid is not completely consistent to the load characteristic of users. Thus, the LAs can provide users with new time-sharing electricity price to improve the benefit of themselves, under the premise of protecting the interests of the users.

Table 2 List of benefits and costs of LA

| Benefits/(CNY) | Costs/(CNY) |
|----------------|-------------|
| saving electricity cost | load-shedding capitalised cost |
| PV | BES |
| BES | DE |
| DE | variable cost |
| electricity sale (to grid) | operating cost |
| electricity sale (to consumers) | maintenance cost |

Table 3 Optimised benefit results

| Consumers’ costs (CNY) | LA’s benefits (CNY) |
|------------------------|---------------------|
| with La | 13,167 |
| without La | 14,669 |

Fig. 3 PV curve and grid’s electricity price

Fig. 4 Comparison of preload and afterload and the DR-price

Fig. 5 Power exchange curve with the grid
The time-sharing electricity price is the key factors influencing the LA scheduling control. The energy storage can absorb energy at valley price and release energy at peak price. Thereby, the abandoning of photovoltaic power is reduced.

In addition, the intermittent and load prediction error of PV will bring new challenges to the decision of LA, and the ratio of PV-energy storage capacity will also affect the efficiency of LA, which deserves further study.

5 Acknowledgments

This work was supported by the Science and Technology Project of SGCC under Grant 52150018000N.

6 References

[1] Xu, Y., Xie, L., Singh, C.: 'Optimal scheduling and operation of load aggregators with electric energy storage facing price and demand uncertainties'. 2011 North American Power Symp., Boston, MA, 2011, pp. 1–7
[2] Xu, Y., Singh, C.: ‘Operation strategies of the load aggregator with electric energy storage’. 2012 IEEE Int. Conf. on Power System Technology (POWERCON), Auckland, 2012, pp. 1–6
[3] Bessa, R.J., Matos, M.A.: ‘The role of an aggregator agent for EV in the electricity market’. Power Generation, Transmission, Distribution and Energy Conversion. IET, 2011, pp. 1–9
[4] Eyer, J.M., Corey, G.P.: ‘Energy storage for the electricity grid: benefits and market potential assessment guide: a study for the DOE energy storage systems program’, Geburthilfe Frauenheilkd., 2010, 45, (5), pp. 322–325
[5] Hung, D.Q., Mithulananthan, N., Bansal, R.C.: ‘Integration of PV and BES units in commercial distribution systems considering energy loss and voltage stability’, Appl. Energy, 2014, 113, (6), pp. 1162–1170
[6] Paterakis, N.G., Erdin, O., BakirtzisA, G., et al.: ‘Qualification and quantification of reserves in power systems under high wind generation penetration considering demand response’, IEEE Trans. Sust. Energy, 2015, 6, (1), pp. 88–103