Electricity ancillary service market model considering demand response of multi-energy load aggregators

Xiang Li¹, Xiang Zheng², Jie Zhang¹, Shaofei Shen³, Haiyue Yu*, Xunhu Yin³

¹ Hangzhou Power Supply Company of State Grid Zhejiang Electric Power Co., Ltd, Hangzhou, Zhejiang, 310016, China.
² State Grid Zhejiang Electric Power Co., Ltd., Hangzhou, Zhejiang, 310007, China;
³ College of Electrical Engineering, Zhejiang University, Hangzhou, Zhejiang, 310027, China;
*E-mail: yuhaiyue@zju.edu.cn

Abstract. Large-scale access of distributed generations, the increasing interconnection of large DC power grids and the demand fluctuation of loads caused by climate change put forward higher requirements for power system stability. The flexible resources on the demand side can respond quickly to meet the needs of power balance of the system. Under the background of the interconnection of multi-energy networks, multi-energy loads (MELs) have become excellent demand response (DR) resources. Firstly, MEL models are established in this paper, including the models for replaceable load, reducible load, transferable load and translational load. Moreover, considering that DR needs to be supported by the ancillary service market, an ancillary service market clearing model with DR provided by MEL aggregators is proposed. Finally, this paper summarizes and prospects the future development of DR with MEL.

1. Introduction

With the rapid development of the power system, more and more renewable energy sources are integrated, resulting in increased volatility and randomness of the power generation. Meanwhile, the inertia of the power system is reducing, which can cause severe frequency fluctuations[1]. The regulation ability of traditional generators has been unable to meet the balance requirement. Therefore, it is necessary to use other means to stabilize the power fluctuation. Demand response (DR) is one of the most used measures which explore the regulation capability in the demand side.

DR is a new development of demand side management in competitive power market. It refers to the market participation behavior that power users respond to the market price signal or incentive mechanism, such as changing consumption pattern. The DR based on electricity price refers to indirectly controlling the operation of load through the change of electricity price in the market combined with consumer psychology and price elasticity[2]. The DR based on incentive means that the power dispatching institution directly controls the load operation and gives incentives and subsidies to the load owners after the response[3]. Various types of DR are put forward, developed and improved with the system reform of electricity market and the progress of power technology[4].

Traditional DR includes user energy storage systems, electric vehicles and thermostatically controlled loads represented by air conditioners and water heaters[5]. They mainly participate in DR through simply load reduction or transfer, which often affects comfort of users. When users are sensitive to comfort changes and do not want to participate in load adjustment, the implementation of
DR is more difficult and the potential is limited. Taking into account the mitigation of power system fluctuations and ensuring the energy using experience of users is the focus and difficulty in the implementation process of DR[6].

The construction of power grid has changed from a traditional grid with one-way energy flow to a smart grid with two-way flow of energy and information. And further integrated with the heat or gas network, it is evolving into a multi-energy internet with power grid as the backbone[7-8]. The coupling of multi-energy enables integrated energy consumers not only to participate in DR through load transfer or reduction, but also in the form of alternative energy use and multi-energy complementary by changing the type of energy use [9]. It is the development trend of multi-energy system.

Nowadays, many researches have been carried out on multi-energy DR. For example, [10] proposed an industrial multi-energy system DR framework and a demand-supply interaction model considering CCHP. DR is carried out through the coupling substitution relationship among cold, heat and electricity. [11] considers carrier DR uncertainty and proposed a probabilistic strategy for energy flow analysis of an integrated multi-energy carrier system to control the risks caused by the uncertainties. [12] extends the application of DR from electricity to multi-energy. To meet the quickly clearing demand of the DR real-time market, a pioneered optimum region method has been proposed.

Most of the above studies are the analysis of the feasibility of implementing multi-energy DR. However, multi-energy load (MEL) resources providing services for the power system through DR requires a good market environment. For the countries with underdeveloped electricity market, they lack the mechanism of demand response resources to participate in the ancillary service market. Moreover, there is a threshold for participation in the electricity market, and a large number of small and medium-sized users cannot participate in the power ancillary service market, so they need to participate in the market through MEL aggregators. In the second section of this paper, the MEL model participating in demand response is introduced. In the third section, a power ancillary service market model including MEL aggregators is proposed. The last section summarizes the full text and looks forward to the development prospect of MELs participating in DR.

2. Models of MEL and MELA

There are a large number of flexible load resources on the demand side, but the power that can be provided is very limited. And it is extremely complicated to organize them to participate in the power market by the power system operator, with huge amount of calculation and strong uncertainty. Therefore, an organization is needed to aggregate the loads within a region and participate in the electricity market as a whole. This organization is the MEL aggregator (MELA). The MELA aggregates a variety of loads, including pure electrical loads such as air conditioners, washing machines, electric vehicles and energy storage. It can also include MELs using multi-energy sources, such as heating devices driven by electricity or gas. From the point of view of load characteristics, it can be divided into replaceable load, reducible load, transferable load and translational load, which are represented in figure 1. The characteristics and models of various loads are described below.

![Figure 1. Four typical types of MEL in multi-energy DR.](image-url)
2.1. Replaceable load model
The replaceable load is a MEL using compound energy. When one kind of energy supply is tight, it
can be switched to other energy supply according to the demand to ensure that the load works
normally during that period of time, such as a heating device heated by electric energy or gas. Hybrid
electric vehicle. The operating characteristics of this kind of load are as follows.

\[
P_{\text{total}}(t) = \sum_{i=1}^{s} P_i(t)
\]

\[
P_i(t) \leq P_{i \text{max}}, \quad i \in S
\]

\[
C_{\text{total}} = \sum_{i=1}^{S} C_i
\]

Where \( P_{\text{total}} \) is the total power required for the operation of the device. \( s \) is the number of types of
energy available for the operation of the device. \( S \) is the collection of available energy. \( P_i(t) \) is power
provided by energy \( i \), \( P_{i \text{max}} \) and \( P_{i \text{min}} \) are the upper and lower limits of energy \( I \) required for the
operation of the equipment respectively. \( C_{\text{total}} \) is the energy cost of device operation, and \( C_i \) is the
consumption of energy \( i \).

2.2. Reducible load model
The load can be reduced is the load that can withstand certain interruption or power reduction and
reduce time operation. It can be partially or completely reduced according to the supply and demand
situation, such as air conditioning and water heater, and the power can be reduced and adjusted by
setting the temperature. Taking air conditioning as an example, the operation characteristics of this
type of load are as follows.

\[
\theta_a(t+1) = R \cdot P_d(t) \cdot k_c \cdot \left(1 - e^{-\Delta t \cdot \xi}\right) + \theta_a(t) \cdot \left(1 - e^{-\Delta t \cdot \xi}\right) + \theta_c(t) \cdot e^{-\Delta t \cdot \xi}
\]

\[
\theta_{\text{min}} \leq \theta(t) \leq \theta_{\text{max}}
\]

\[
P_{d,\text{min}} \cdot s(t) \leq P_d(t) \leq P_{d,\text{max}} \cdot s(t), \quad P_{d,\text{min}} < P_{d,\text{max}}
\]

Where \( R \) is the thermal resistance of the room. \( k_c \) is the energy conversion coefficient. \( \xi \) is a
constant related to the heat capacity of the room. \( \theta_{\text{max}} \) and \( \theta_{\text{min}} \) are the upper and lower limits of the
temperature in the room respectively. \( P_{d,\text{max}} \) and \( P_{d,\text{min}} \) are respectively the upper and lower limits of
the electrical power of the equipment. At time \( t \), \( \theta_a(t) \) and \( \theta_c(t) \) are the temperature in and out the
room respectively. \( s(t) \) is a 0-1 variable, where 1 means the device is on and 0 means the device is
off. \( P_d(t) \) is the electrical power consumption of the equipment.

2.3. Transferable load model
The electricity consumption of the transferable load can be adjusted flexibly during the period of
electricity consumption. The interruption is allowed during the period of electricity consumption and
the duration is not fixed. As long as the total load demand before and after the transfer remains
unchanged, such as electric vehicle, which has the property of energy storage, its operation
characteristics can be described by the following equations.

\[
C(t+1) = K \cdot P_d(t) + C(t)
\]

\[
\alpha_{\text{min}} C_b \leq C(t) \leq \alpha_{\text{max}} C_b
\]

\[
P_{d,\text{min}} \leq P_d(t) \leq P_{d,\text{max}}
\]
Where $K$ is the conversion coefficient between battery energy consumption and energy storage. $\alpha_{\text{max}}$ and $\alpha_{\text{min}}$ are respectively the upper and lower limits of battery energy storage percentage. $P_{d,\text{max}}$ and $P_{d,\text{min}}$ are the upper and lower limits of charge and discharge power respectively.

2.4. Translational load model

The power consumption period of the movable load is flexible, but it cannot be interrupted during the working period. The starting time of the load can be reasonably planned according to the running time range of such load, so as to optimize the household power consumption management. Such as washing machines, dishwashers, rice cookers and so on. The model is as follows.

$$P_d(t) = s(t)P_n$$

$$s(t) = 0, \quad \forall t \notin [t_s, t_e]$$

$$\sum_{t=t_s}^{t+T_p} s(t) \geq T_s \cdot \left( s(t+1) - s(t) \right), \quad t \in [t_s - 1, t_e - T_s]$$

$$\sum_{t=t_s}^{t+\lambda} s(t) \geq 1, \quad 0 < \lambda < t_e - t_s - T_p$$

Where $P_n$ is the rated power consumption of the electrical appliance. $[t_s, t_e]$ is the running time interval of the equipment. $T_s$ is the duration of operation of the device. $\lambda$ is the maximum delay time set in advance by the user, and $\lambda = 0$ for non-delay devices.

2.5. MELA model

Due to the aggregation of a large number of different kinds of loads, the internal characteristics of MELA are complex. But from a view of power system, MELA has an external characteristic of a simple whole.

$$P_{\text{e, total}}(t) = \sum_{x \in X} P_{e,x}(t), \quad X = \{\text{replac}, \text{reduc}, \text{transf}, \text{transl}\}$$

Where $P_{\text{e, total}}(t)$ is the total electric power cost of MELA. $P_{e,x}(t)$ is the electric power cost of load $x$, which is one of replaceable load, reducible load, transferable load or translational load. That is the total electric power of MELA is a summary of electric power of four types of multi-energy loads. When $x = \text{replac}$, $P_{e,x}(t)$ is constrained by (1)-(3). When $x = \text{reduc}$, $P_{e,x}(t)$ is constrained by (4)-(6). When $x = \text{transf}$, $P_{e,x}(t)$ is constrained by (7)-(9). When $x = \text{transl}$, $P_{e,x}(t)$ is constrained by (10)-(13).

3. Electricity ancillary service market model with MELA

At present, electricity ancillary service market clearing mechanism is mainly divided into two ways. One of the two ways is sequential clearing mechanism of spot electric energy and ancillary service market, such like real-time market of PJM[13] and ISO-NE[14]. And the other way is joint clearing mechanism, such like day-ahead market of CAISO[15] and MISO[16]. The second way can get the overall optimal planning, thus a joint clearing mechanism of spot electric energy and ancillary service market for day-ahead market is proposed in this section.

Members participating in the electricity market are power generators, MELAs and power system operators. Because a single load cannot directly participate in the market, the behavior in the electricity market is reflected by MELAs.

In the medium-and long-term ancillary service market, part of the ancillary service capacity can be sold by centralized bidding, and the winning generator unit and MELA must participate in the day-ahead and real-time ancillary service market, and obtain capacity income according to the available capacity, which is helpful to guide the investment in demand response.

4
In the day-ahead market, MELAs offer electricity quotation curve with decreasing electricity consumption, as well as ancillary services. At this time, the generator unit commitment, unit output and ancillary services are jointly optimized, and the goal is to minimize the total social cost, which can be expressed as (15).

\[
\min \left[ \sum_{i=1}^{T} \sum_{l=1}^{I} \left[ C_{Gi} \cdot s_{Gi}(t) \cdot (1-s_{Gi}(t-1)) + C_{Gi,l}(P_{Gi}(t)) \right] + \sum_{i=1}^{T} \sum_{j=1}^{I} \left[ C_{RDj}^{u} (E_{RDj}^{u}(t)) + C_{RDj}^{d} (E_{RDj}^{d}(t)) \right] \right] - \sum_{i=1}^{T} \sum_{j=1}^{I} B_{ij}(P_{ij}^{o}(t)) \right) (15)
\]

Where \( T \) is the number of periods, \( I \) is the number of generators, \( SU_i \) is the start-up cost of generator \( i \), \( s_{Gi}(t) \) is the start-up and shutdown state of generator \( i \) at time \( t \), \( s_{Gi}(t) = 1 \) while generator \( i \) is start-up and \( s_{Gi}(t) = 0 \) while generator \( i \) is shut-down. \( P_{Gi}(t) \) is the power of the generator \( i \), \( F_{Gi}(P_{Gi}(t)) \) is the operating cost of generator \( i \). \( E_{RDj}^{u}(t) \) and \( E_{RDj}^{d}(t) \) are the up and down adjustment of generator \( i \), respectively. \( C_{RDj}^{u}(E_{RDj}^{u}(t)) \) and \( C_{RDj}^{d}(E_{RDj}^{d}(t)) \) are the cost of up-adjustment and down-adjustment of ancillary services for generator \( i \), respectively. \( K \) is the number of MELAs providing ancillary services. \( E_{DRj}(t) \) is the reserve capacity, \( C_{DRj}(E_{DRj}(t)) \) is the cost of ancillary services for MELAs. \( M \) is the number of MELAs. \( P_{ij}^{o}(t) \) is the power provided by MELAs. \( B_{ij}(P_{ij}^{o}(t)) \) is the generation or consumption benefits of MELAs.

In the safety constraint unit commitment optimization model of the day-ahead market, the constraints mainly include system power flow equation, tie line cross-section power flow constraint, minimum start-stop constraint, unit output constraint, unit climbing constraint, reserve capacity constraint and so on.

3.1. Bus power balance constraint

\[
\sum_{i=1}^{I} P_{Gi}(t) + \sum_{k \in e(i)} P_{fk}(t) = \sum_{j \in e(i)} P_{kj}(t), \quad t = 1,2,\ldots,T
\]

Where \( r \) is a set of system network nodes. \( e(i) \) is the set of branches connected to bus \( i \). \( P_{kj}(t) \) is day-ahead prediction of power of load \( j \). \( P_{fk}(t) \) is the power injected into bus \( i \) by tie-line \( k \).

3.2. Tie line power flow constraint

\[
-P_{max} \leq P_{k}(t) \leq P_{max}, \quad t = 1,2,\ldots,T
\]

Where \( P_{k}(t) \) is the tie line power flow on tie-line \( k \), and \( P_{max} \) the maximum power transmission of tie line.

3.3. Minimum start-stop constraint

\[
(s_{Gi}(t-1) - s_{Gi}(t) + s_{Gi}(t+\lambda) - s_{Gi}(t+\lambda-1)) \leq 1, \quad \forall \lambda \in [1,\ldots,D_i-1]
\]

\[
(s_{Gi}(t) - s_{Gi}(t-1) + s_{Gi}(t+\lambda-1) - s_{Gi}(t+\lambda)) \leq 1, \quad \forall \lambda \in [1,\ldots,O_i-1]
\]

Where \( D_i \) is the minimum downtime of unit, and \( O_i \) the minimum start-up time of the unit.

3.4. Generator output constraint

\[
P_{Gi}(t) + E_{RDj}(t) \leq P_{Gi}^{\max}, \quad t = 1,2,\ldots,T
\]

\[
P_{Gi}(t) - E_{RDj}(t) \geq P_{Gi}^{\min}, \quad t = 1,2,\ldots,T
\]

Where \( P_{Gi}^{\max} \) and \( P_{Gi}^{\min} \) are the maximum and minimum power output of the generator, respectively.
3.5. Unit climbing rate constraint

\[
0 \leq E_{Rgi}^u(t) \leq \Delta P_{Gi}^u
\]
\[
0 \leq E_{Rgi}^d(t) \leq \Delta P_{Gi}^d
\]

Where \( \Delta P_{Gi}^u \) and \( \Delta P_{Gi}^d \) are the maximum uphill and downhill rates of the generator, respectively.

3.6. Reserve capacity constraint

\[
\sum_{i=1}^{I} E_{Rgi}^u(t) + \sum_{j=1}^{J} E_{Rdy}(t) \geq E_R^u
\]
\[
\sum_{i=1}^{I} E_{Rgi}^d(t) \geq E_R^d
\]

Where \( E_R^u \) and \( E_R^d \) are the minimum up reserve capacity and the minimum down reserve capacity of the system, respectively.

3.7. Capacity constraints of reserve of MEGA

\[
0 \leq \sum_{j=1}^{J} E_{Rdy}(t) \leq \alpha \cdot E_R^u
\]

Where \( \alpha \) is the proportion of the reserve capacity of the MELA in the up-regulation of the reserve capacity of the system. Due to the uncertainty of MELAs, the proportion of MELAs in the reserve capacity of the system is limited to ensure the safety and reliability of the system. For example, in the electricity market of the Electric Reliability Council of Texas, The proportion of response capacity provided by demand-side resources is limited to 50% of total, that is \( \alpha = 50\% \).

3.8. MELA output constraint to provide electricity quotation

\[
P_j \leq \overline{P}_j(t) \leq \underline{P}_j
\]

Where \( \overline{P}_j \) and \( \underline{P}_j \) are the maximum power and minimum power of MELA \( j \) respectively.

4. Conclusions

This paper extends the demand response from the pure electric load to the MEL, further excavates the demand response capability of the system and reduces the impact on user comfort. Firstly, four models of MEL participating in demand response are proposed, including replaceable load, reducible load, transferable load and translational load. Then a model of MEL participating in power ancillary service market through load aggregators is proposed. Allowing MELs to participate in the market through MELA lowers the threshold of market entry, which will make more resources participate in the demand response of the power system and improve the regulation ability of demand response.

The development of electrical network to the interconnection of multiple networks is a general trend, and the integrated energy Internet will be the form of energy network in the future. The MEL has the characteristics of rapid response and little influence on user comfort, so it is an excellent resource for demand response in the future. However, there are still some problems in its specific application, such as: the load baseline in the electrical demand response is a non-stop research point, and how to determine the baseline in the MEL demand response. The cooperative control strategy of large-scale MEL group response is also a research difficulty. The transformation of a large amount of electric energy, like other energy sources, is bound to exert pressure on other energy supplies, and even leads to the stability of the energy system.

The implementation of MEL demand response needs the joint efforts of many aspects. On the one hand, the initial application of integrated energy equipment is relatively expensive, gradually replace the electricity load and participate in the demand response needs strong support from the government,
such as the introduction of subsidies, incentive policies. On the other hand, energy companies should also give full play to the role of the market, guide the growing MEL to participate in the regulation of the system, and tap more value from the user level.

Acknowledgements
This research is supported by the science and technology project (Research on key Technologies of coordinated Control of Integrated Energy Interactive Operation in spot Market Environment, 5211HZ200008) of State Grid Zhejiang Electric Power Co. Ltd.

References
[1] Xie, K., Hui, H., and Ding, Y. (2019) Review of modeling and control strategy of thermostatically controlled loads for virtual energy storage system Prot. Control Mod. Power Syst. 4 23
[2] Zhao, Z., Wu, L. and Song, G. (2014) Convergence of Volatile Power Markets With Price-Based Demand Response IEEE Trans. Power Syst. 29 2107–18
[3] Zhong, H., Xie, L. and Xia, Q. (2013) Coupon Incentive-Based Demand Response: Theory and Case Study IEEE Trans. Power Syst. 28 1266–76
[4] Albadi, M. H. and El-Saadany, E. F. (2007) Demand Response in Electricity Markets: An Overview In: 2007 IEEE Power Engineering Society General Meeting. Tampa. pp 1–5
[5] Yu, H., Xie, K., Hui, H. and Ding, Y. (2020) Review and Prospect of Flexible Loads for Participating in Frequency Regulation. In: 2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2). Wuhan. pp 2605–8
[6] Good, N., Karangelos, E., Navarro-Espinosa, A. and Mancarella, P. (2015) Optimization Under Uncertainty of Thermal Storage-Based Flexible Demand Response With Quantification of Residential Users' Discomfort IEEE Trans. Smart Grid 6 2333–42
[7] Hannan, M. A., Faisal, M., Ker, P. J., Mun, L. H., Parvin, K., Mahlia, T. M. I. and Blaabjerg, F. (2018) A Review of Internet of Energy Based Building Energy Management Systems: Issues and Recommendations IEEE Access 6 38997–9014
[8] Dong, Z., Zhao, J., Wen, F. and Xue, Y. (2014) From smart grid to energy internet: Basic concept and research framework Dianli Xitong Zidonghua Automation Electr. Power Syst. 38 1–11
[9] Bahrami, S. and Sheikhi, A. (2016) From Demand Response in Smart Grid Toward Integrated Demand Response in Smart Energy Hub IEEE Trans. Smart Grid 7 650–8
[10] Jiang, Z., Ai, Q. and Hao, R. (2019) Integrated Demand Response Mechanism for Industrial Energy System Based on Multi-Energy Interaction IEEE Access 7 66336–46
[11] Massrur, H. R., Niknam, T. and Fotuhi-Firuzabad, M. (2018) Investigation of Carrier Demand Response Uncertainty on Energy Flow of Renewable-Based Integrated Electricity–Gas–Heat Systems IEEE Trans. Ind. Inform. 14 5133–42
[12] Shao, C., Ding, Y., Siano, P. and Lin, Z. (2019) A Framework for Incorporating Demand Response of Smart Buildings Into the Integrated Heat and Electricity Energy System IEEE Trans. Ind. Electron. 66 1465–75
[13] PJM. (2021) PJM Manual 11: Energy &amp; Ancillary Services Market Operations. https://www.pjm.com/directory/manuals/m11/index.html#about.html
[14] ISO-NE. (2021) Market Rule 1: Transmission, Markets and Services Tariff Section III Sections 1-12. https://www.iso-ne.com/static-assets/documents/2014/12/mr1_sec_1_12.pdf
[15] CAISO. (2012) California ISO - Market Processes. http://www.caiso.com/market/Pages/MarketProcesses.aspx
[16] MISO. (2020) Business Practices Manuals: BPM 002 - Energy and Operating Reserve Markets. https://www.misoenergy.org/legal/business-practice-manuals/