Overview of the Load-source Duality Modeling for Demand Side

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Abstract. With the increase of load and clean-green energy connect to the power system, big challenges are brought to the traditional control method of generation-follows-load (GFL). Therefore, it is important to study the load-follows-generation (LFG) models which can achieve active demand response by changing the load temporarily to reduce the difference between maximum and minimum load. This paper introduces the concept of LFG and GFL models, summarizes the difference between them and puts forward the concept of load-source duality at first. Then, introduces load response modeling, optimization objectives, constraints, scheduling methods and control methods of six LFG models based on the recent research results in this area. Each model can alleviate the pressure in maintaining stability on the generation side, improving the safety and reliability of the power system. Finally, this paper puts forward the future development trend of LFG models based on the overviews.

Keywords: LFG models; Load-source duality; Flexible load modeling; Demand respond.

1. Introduction
China announced to peak the carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. In order to achieve this goal, the power system has to focus on raising the proposing of using clean-green energy instead of using coal and fossil to generate electricity in industrial manufacturing, construction and transport. State Grid Corporation of China plans to increase using clean energy such as wind, solar and hydro-power in primary energy consumption to 20 percent by 2025 and 25 percent by 2030.

Traditional power system modeling is power generation follows the change of load (GFL). With the massive access of distributed power generation and the continuous growth of load, big challenges are brought to the traditional power system. Different from the traditional power system, the modern smart power system is greener and cleaner with the connection of distributed generators and flexible loads [1]. The smart power system has a characteristic of load-follows-generator (LFG) and the role of flexible loads varies with the price signal and incentive mechanism [2]. LFG forms a load model with dual attributes of ‘load’ and ‘power’ through load aggregation. This duality load model of load-source is the basis of supporting the active demand response.

This paper first introduces the concept, operation mechanism and function of LFG model. Then classifies and compares some LFG models according to different research objects, focuses on the practical application of load aggregation. Finally puts forward the future development direction of LFG model.
2. Concept and Function of LFG

Traditional control model is GFL (shown in Figure 1). GFL model gathered the load of users through load aggregation. Then use primary and secondary frequency control to maintain frequency and balance active power, use reactive power supplies to maintain system voltage and balance reactive power. This load aggregation equations are:

\[ P_A = \sum_{k=1}^{K} (P_k)_{measured} \]
\[ Q_A = \sum_{k=1}^{K} (Q_k)_{measured} \]

\( P_A \) and \( Q_A \) is the active and reactive power after aggregation; \( (P_k)_{measured} \) and \( (Q_k)_{measured} \) is the measured value of user k’s load requirement.

With the mechanism improvement in electricity market competition, loads of distributed generators are connected to the power system. Depending only on the traditional generators to maintain system stable is impractical, tremendous pressure is brought to the system. In this way, the LFG model with load-source duality is proposed. It can vary the loads to match the output power of generators. LFG model, which is shown in figure 2, can fully considered the demand response from flexible-load when load aggregates. The electricity consumption behavior of the demand side will be changed by the electricity price or policy. The load of the demand side will meet the preset settings in a certain period, in order to relive the pressure of stabilizing the generation side and improve the reliability of power system.

LFG model has three functions. The first function is to realize the active demand response. The load-source duality of LFG model enhances the interaction ability of users and the power grid. With the further development of smart grid and demand side management, the flexible-load can be considered as a schedule resource for the generation side in order to realize the active demand response.

The second function is to smooth the load curve. LFG model can reduce flexible-load at peak period and increase flexible-load at off-peak period. This demand side management will reduce the peak and valley value, smooth the load curve, and improve the safety of the power grid.

The third function is to promote renewable energy consumption, reduce the investment of generators and energy storage device. The increase in connecting distributed renewable energy into the power system brings randomness and unpredictability harm to the power system. The use of LFG model can management flexible-load to meet the power generation curve and reduce the abandonment of wind and solar power. On the other side, the use of LFG model can improve the economy of the power system by reducing the number and investment of energy storage device.
3. Different Aggregation Models of LFG

This paper classifies the LFG models in 6 ways. The load aggregation model shows the scheduling potential of different load-types. It reflects that the load can be as ‘source’ and ‘load’ at the same time, which is called load-source duality. The ‘load + energy storage device’ and ‘load + generator’ can be formed as virtual battery and virtual power plant, which can compensate the randomness and unreliability of load scheduling. These models can be better integrated into the power grid and realize energy interaction with other regions.

3.1. Load Aggregation Model

Load behavior is highly random and uncontrollable. Researchers trying to establish a variety flexible-load response and control models by studying the electricity historical data and user behavior. The variety flexible-load response and control models can understand the potential of electricity scheduling and develop a coordinated scheduling plan.

Load aggregation model is a double layer optimization model, which includes flexible-load operation model and power sales decision model [4]. Flexible-load operation model is established on the user side. Its goal is to optimize the power consumption cost and transmit the total electricity demand information to the aggregator. Aggregator has the goal of maximizing its own economic income. The power sales decision model will transfer the dynamic price information to users from the aggregator. These two models combined together to form a two-layer iterative model of mutual coordination on the sales side [5][6]. The objective function in aggregator is:

\[
\max \{ P_A(t) = \sum_{k=1}^{n} P_k(t) \}
\]

\[
\min \{ P_D(t) - P_A(t) \}
\]

\[
(3)
\]

\( P_A(t) \) represents the total loads in the aggregator, which may include thermal load, electric vehicle, interruptible load, transferable load and conventional loads. \( P_D(t) \) is the power allocated to the aggregator at time \( t \).

3.2. Load + energy Storage Aggregation Model

In practice, the LFG model reduces the power demand at the peak period, which is equivalent to increasing the positive standby capacity of the system. On the contrary, the LFG model can also increase the incentive load at off-peak period, which is equivalent to increasing the negative standby capacity of the system. This kind of model is related to the user response and it is not stable. Therefore, many literature combined the load and energy storage together to model in order to optimize the load curve. The load and energy storage aggregation model work like virtual battery. The function is:

\[
P_t^{\min} \leq P_t \leq P_t^{\max}
\]

\[
E_t^{\min} \leq E_t \leq E_t^{\max}
\]

\[
E_{t+1} = E_t + P_t \Delta t
\]

\[
(4)
\]

\[
(5)
\]

\[
(6)
\]

\( P_t \) and \( E_t \) are the power and energy for virtual battery at time \( t \). \( P_t^{\min}, E_t^{\min}, P_t^{\max}, E_t^{\max} \) are the minimum and maximum value for battery power and energy.

3.3. Load + renewable Energy Aggregation Model

Since wind power and solar power are greatly affected by the weather and geographical location, the uncertainty and uncontrollable are brought to the power system. In order to increase the usage of renewable energy, it is important to understand the different power curve of renewable energy.

For wind power, the forecast of output energy is uncertain since the forecast is based on the historical data. LFG adjusts the load operation mode to promote the wind power consumption. While the wind power output is less than the predicted value, the load-source duality of load can be used to see the interrupted load as the system positive standby, which is equivalent to increasing the standby capacity of the generator and reducing the investment [7]. While the wind power is bigger than the actual load,
the way to balance the power system is to use the transferable load to fill the off-peak period. The objective functions are:

\[
\min \mathcal{F} = F_t + F_i + F_p
\]

\[
F_t = f_3 \left( C_{G,t,i}, C_{UG,t,i}, U_{G,t,i} \right)
\]

\[
F_i = \sum_{t=1}^{T} \left( \sum_{l=1}^{n} C_{i,t,l} \right)
\]

\[
F_p = \sum_{t=1}^{T} \left( P_{LS,t} \times \eta_{LS} + P_{WS,t} \times \eta_{WS} \right)
\]

\(C_{G,t,i}, C_{UG,t,i}, U_{G,t,i}\) are the operation cost, start-up cost and operating status of traditional generator unit \(i\). \(C_{i,t,l}\) and \(C_{P,t,i}\) are the incentive-type and price-type demand response costs. \(P_{LS,t}\) and \(P_{WS,t}\) are the load reduction and wind abandonment. \(\eta_{LS}\) and \(\eta_{WS}\) are the unit price of load cutting and wind abandonment punishment.

For the solar power, the photovoltaic power generation varies according to the geographical location. The scheduling mode is roughly the same as the above. The photovoltaic operator cost and photovoltaic consumption rate have the objective function as follows:

\[
F_{PV} = \sum_{t=1}^{T} \left( \eta_d P_{d,t} + \eta_e P_{e,t} + \eta_{PV} P_{PV,t} \right)
\]

\[
S_{PV} = \frac{E_{SC} + E_{FC}}{\sum_{t=1}^{T} P_{PV,t}}
\]

\[
E_{SC} = \sum_{t=1}^{T} \min \left\{ P_{PV,t}, P_{d,t} \right\}
\]

\(\eta_d, \eta_e\) and \(\eta_{PV}\) are the electricity price of user, on-grid electricity price of solar power and photovoltaic subsidized electricity price. \(P_{d,t}, P_{e,t}\) and \(P_{PV,t}\) are the load power, on-grid power of solar, and output power of photovoltaic. \(E_{SC}\) is the solar power consumption by the load, \(E_{FC}\) is the solar power consumption by the flexible capacity energy storage.

3.4. Load + energy storage + renewable Energy Aggregation Model

Though the electrical energy storage equipment has the characteristic of high cost and limited capacity, it is still widely existed in the power system in order to maintain the system stability. Relate researches include multiple research objects, integrating renewable energy resources, energy storage system, controllable load, conventional load through advanced control, measurement, communication and other technologies. It achieves the minimum total social cost by treated the demand side resources, which has the load-source duality characteristic, equally with supply side resources [8][9].

For wind power consumption, Xudong et al. [10] establishes a joint model of nuclear-fire-VPP (Virtual power plant) in the power grid with nuclear power units occupying a relatively high proportion. During the power system operation, the energy storage equipment produces energy interaction with the control center and the equipment loss will be caused by the charging and discharge process. The operation and maintenance cost generated by the energy storage equipment is:

\[
\begin{align*}
F_{et} & = \eta_e |P_{et}| \\
P_{et} & = -P_{etin} + P_{etout}
\end{align*}
\]

\(\eta_e\) is operation and maintenance price. \(P_{et}\) is the output energy of storage equipment during \(t \) period. \(P_{etin}\) and \(P_{etout}\) are the charging and discharge power of the energy storage equipment respectively.

As for the absorption of photovoltaic power, Jiechen et al. [11] quantifies uncertain distributed energy with a robust boundary VB (virtual battery) model, use a determination model for energy storage and daily load, and use Minkowski sum to model VB. Nan et al. [12] aims at the price-sensitive load, puts forward the energy storage charging and discharge strategy and micro network optimization operation strategy to reach the goal of maximum the efficiency of photovoltaic utilization rate and maximum annual net profit. This paper solves the user adjustment behavior and energy storage operation strategy under the peak and valley electricity price.
3.5. Power to Gas Technology

Power to gas (P2G) uses the surplus electric power to generate hydrogen. It also can use CO2 to make methane and provide gas to consumers [13]. LFG can also work with this technology. Liwei et al. [14] designed a P2G-based virtual plant structure that integrates P2G systems and storage tanks into VPP. The result shows that the flexibility of power system operation can be improved by using P2G and price-based demand response.

3.6. CCHP Models

Combined cooling, heating and power (CCHP) uses methane as the main fuel to drive gas power generators to generate electricity and provide the waste heat to users as well. CCHP improves the primary energy utilization rate of the whole system and increases the economic benefits [15]. A large number of literatures has applied LFG model in this technology. These researches considering multi-types of demand respond loads such as renewable energy units, gas turbine units, energy storage devices and P2G equipment.

Some of the literature conducts research within a specific area, including multi-types of demand response flexible load and obtains the demand-side load coordination strategy [16][17]. Some of the literature focuses on studying inter-regional energy sharing. Feilong et al. [18] proposes a full-cycle power fluctuation suppression strategy of distributed CCHP systems, which contains thermal load and battery energy storage models. Peng et al. [19] establishes a quantitative model considering flexible load such as CCHP, EV, thermal load to simulate a multi-comprehensive energy building.

4. The Future Work for LFG Aggregation Model

4.1. Demand-side Market Mechanism

The LFG model at the demand side can guide users to develop reasonable comprehensive energy utilization plans, enabling users to respond to the power market price signals and adjust the energy demand and consumption habits.

On the other hand, the LFG model has advantages such as increase energy efficiency, lower energy consumption costs and obtaining additional economic benefits. However, in some cases the optimization results will increase the total energy costs and affect the enthusiasm of users to respond to LFG scheduling [20]. This result reflects the differences in optimization objectives between users and electricity selling companies.

At present, there is less collaborative optimization research on users and electricity selling companies. The way to coordinate the interests of various parties on the power distribution side and realize the mutually beneficial market mechanism is the main point of future research.

4.2. Load Scheduling Technology of Multi-timescale

Errors are existed in the system load prediction, network topology may also change especially with a large number of intermittent energy accesses. It is difficult to ensure the accuracy and practicability of the recent plan. In addition, the user response also has uncertainty. The potential impact of the response uncertainty will increase with the number of loads involved in the scheduling. Therefore, it is necessary to modify the scheduling plan on the timescale based on the rolling updated load and renewable energy real-time data. Real-time planning and response resources is still the focus of perfect load scheduling technology.

4.3. Multi-agent Scheduling Mechanism

The personalized needs and privacy behavior of the electricity consumers will influence the optimization decision of the LFG model. Due to privacy considerations, it is difficult for the power system operators to get the information of the usage amount of consumers. Thus, a multi-agent scheduling mechanism is derived [21]. The current research of multi-agents in GFL models are inadequate, including the optimization of multi-energy coordination among multiple agents and the centralized or distributed unified optimization.
5. Conclusion

LFG model has the characteristic of load-source duality and it is more economic and environmental friendly than the GFL model. Guiding flexible loads to participate in power system operation and dispatching, the power system regulation ability can be effectively enhanced. Using the GFL model in the power system can improve the safety and economy of power system operation, and the renewable energy consumption can be promoted to realize the clean energy.

The development process of demand response technology in recent years is comprehensively studied in this paper, and the LFG model is mainly reviewed. The main conclusions are as follows:

(1) A major feature of smart system is to realize the load-follows-generation dispatching mode. Traditional GFL model simply aggregated and added the measured load together. The LFG model, on the basis of load aggregation, classified the loads and aggregated them to form a double-layer structure of information transmission between power companies to aggregators, and aggregators to users. The controllable capacity of aggregated loads can be changed by changing the control variables of adjustable capacity.

(2) The development direction of LFG model based on the concept of load-source-duality is proposed. This paper pointed out that price and incentive are the key factors to realize LFG model and active demand response. Optimization objectives are different but the main purpose is using less money to produce clean electricities to the customer. The regional power system with multiple flexible loads, energy storage equipment and distributed generation can be aggregated into VPP model to realize energy interaction between regions.

(3) Future research can first be carried out in the aspect of demand side coordination to realize the mechanism of mutual benefit on the demand side. Secondly, the scheduling mode can be studied to keep the system balanced and cost less when the large number of intermittent energy access into the power system.

With the further application of Internet of Things technology in power system, it is an important development direction of new energy power system in the future to change the traditional dispatching mode dominated by GFL model and develop more dispatching modes dominated by LFG model.

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