# 1

# Background

## 1.1 Power Management

With the development of smart grids and the deep interconnection of multiple large-scale regional power grids, power systems are considered as the largest artificial networks that have ever been built. Power systems include coupled primary/secondary power equipment and are supported by advanced control technology and efficient communication networks to form an intelligent autonomous system. To meet the high-performance requirements from all aspects, power management is of great importance in the smart grid. On the one hand, with the increasing penetration level of distributed energy generators, the dispatchable power generation will be relatively less as the renewable energy generation has the characteristics of high uncertainty and intermittency. In order to realize the real-time supply-demand balance between power generation and consumption, effective power generation scheduling strategies should be designed to accommodate the integration of distributed energy resources. On the other hand, flexible and controllable loads can interact with the power grid through the smart meter, which is an important link to ensure the real-time balance between grid power generation and consumption. Thus, load-side power management plays a more important role.

The power management in the smart grid is to optimize the energy utilization efficiency by coordinating the various controllable units of the power grid through efficient communication network and advanced control techniques to ensure the safe, stable, reliable, and efficient operation of the entire power grid. Power management can be classified into multiple problems according to different objectives, time scales, and control targets. Proper and effective control strategies are the key to achieve safe, reliable, stable, efficient, and flexible operation of the power grid.

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In addition to the basic objectives of ensuring system stability, the power management in the smart grid also includes the following objectives:

(1) Enable the proportional distribution of active/reactive power output of distributed energy resources;
(2) Ensure that the voltage amplitude and frequency are kept within the allowable range and compensate for the fluctuations of the distributed energy generators output and the dynamic load power demand;
(3) Reduction of the circulating current between distributed energy resources and realize the desired power exchange with the external power grid;
(4) Be adaptive to the plug-and-play feature and the system topology changes;
(5) Participate in the regulation of the power market, realize the optimal scheduling and coordinated power allocation, and provide various auxiliary services when necessary; and
(6) Identify the topology of the smart grid promptly.

The above objectives require that the power grid, the distributed energy resources, and the controllable loads within the system coordinate their respective control decisions with each other to achieve this. To achieve the above objectives, many scholars propose a hierarchical control structure. The primary control layer aims to maintain the stability of the voltage, frequency, and output power according to the control command of the system. Distributed energy resources should select specific control strategies based on their characteristics and control mode. When no frequency and voltage support is required, the distributed energy resources operate in the constant power output mode. The existing coordination mechanisms of multiple distributed energy resources can be divided into master–slave control and peer-to-peer control mode. In the master–slave mode, the master-distributed energy resource with the largest generation capacity is controlled with constant voltage and frequency mode to provide voltage and frequency support to the power system. Other slave-distributed energy resources are controlled under the constant power mode to maintain the active/reactive power balance. In the peer-to-peer mode, the distributed energy resources are all controlled based on the droop control to maintain the stability of the voltage, frequency, and the active/reactive power balance in the power system by simulating the active frequency characteristics and reactive voltage characteristics of the conventional generator because droop control strategies can achieve power sharing by adjusting the droop coefficient and do not require any information exchange.

The secondary control layer aims to realize the regulation of voltage and frequency and focus to research on the first two aspects. Because the master distributed energy resource device in the master–slave control mode may not have enough capacity to compensate for the power fluctuations, the droop control in the peer-to-peer control mode essentially results in poor performance, the generation or load change will cause the system voltage and frequency deviations. The accumulated deviations of voltage and frequency may lead to the collapse of power systems, so it is necessary to adjust the distributed energy resources to eliminate the deviations and improve the overall dynamic performance of the power system. In addition, in the frequency droop control, the active power can be accurately shared among multiple distributed energy resources. However, in the voltage droop control, the reactive power sharing usually leads to unreasonable distribution because of the inconsistent output impedances of the inverters. Inaccurate reactive power sharing affects energy efficiency and the life span of power electronic equipment and causes current circulation, which will seriously impact the system reliability, stability, and economy. Generally, conventional power systems adopt centralized control strategies to achieve the secondary control target.

Recently, different control methods have been proposed for the implementation of secondary frequency and voltage control. Because the frequency is a global variable, it can either be controlled via a centralized or distributed method based on direct or indirect access to the global information or a decentralized control based on the local measurement. Although the voltage output of the inverter is a local variable, in order to achieve the accurate reactive power sharing and voltage recovery of the power system, the secondary voltage control is mainly centralized and distributed depending on the system information interaction.

The tertiary control layer aims to optimize the power grid economic operation and energy management. The total operating cost of the power systems is minimized, and the distributed energy resources utilization efficiency is maximized while ensuring a stable and reliable operation. There exist plenty of literature studies on tertiary energy management in terms of economic dispatch, demand response, and loss minimization, which can be mainly divided into three categories. The first category is the analytical methods, such as lambda iteration, linear, and nonlinear programming. The second category is the heuristic methods such as hybrid immune algorithm, particle swarm optimization, ant colony optimization, etc. The third category is the distributed optimization approaches, which only require information exchange through a sparse communication network and can achieve optimal or near-optimal solutions while satisfying various local and coupled constraints.

## 1.2 Traditional Centralized vs. Distributed Solutions to Power Management

Traditionally, the stable and economic operation of power systems has been achieved primarily through centralized or decentralized control with the little involvement of the distributed coordinated control. The existing centralized energy management requires each user and power generator to send the local information to the control center. After collecting all the information, the control center processes a huge amount of data and makes control decisions, and then decisions are transmitted to the local users and the power generation units. The centralized control structure has the advantages of simplicity, high convergence accuracy, and fast convergence.

These centralized approaches have been effective so far for conventional power systems. However, they may face severe challenges to manage future power systems with a high penetration level of distributed energy resources because of the following reasons. First, the centralized approaches require sophisticated communication infrastructure between the central controller and every single unit in the power network to collect information globally and a powerful central controller to process huge amount of data and make complicated control decisions. Thus, these solutions are computationally and communicationally expensive for implementation and highly rely on the capability and reliability of the control center, so they are less robust to single-point failures. Second, different vectors need to coordinate each other's respective control decisions to achieve the global system objective in the future power systems where participants may not be willing to reveal private information such as their generation and utility cost functions and power consumption patterns. Third, the operating conditions of the power systems may change rapidly and frequently because of the unexpected supply-demand imbalance and lowered inertia caused by the increasing penetration level of power electronics-based control devices, and centralized control approaches may not be able to respond in a timely manner.

In order to obtain the accurate state information of the power systems in real-time, the deployment of measuring equipment in the smart grid will continue to increase, resulting in a sharp increase in the amount of data that the control center needs to collect, and the limited communication resources, resulting in an increase in data transmission delay and a high communication cost. The traditional centralized control methods usually subject to poor scalability and cannot meet the requirements of accurate control of the smart grid with satisfying dynamic performance in a real-time manner. With the expansion of power system scale and the increasing number of controllable objects, distributed control gradually shows its superiority in terms of robustness and low control cost.

Compared with centralized control, distributed control has the following advantages: (i) Global optimal or near-optimal system objective is achieved based on a point-to-point sparse communication network, which reduces communication burden, (ii) parallel data processing and calculation is done without the central controller, which lower the computation cost significantly, (iii) the "plug and play" function is supported, which also facilitates scalable application to large systems, and (iv) control decision is made by a local control unit, which improves reliability. Therefore, distributed energy management approaches are more suitable for the cooperation of large-scale distributed intelligent equipment in vast geographical areas to ensure safe, stable, and economic operation of the smart grid, which has received extensive attention from worldwide researchers and scholars.

## 1.3 Existing Distributed Control Approaches

In recent years, distributed control and distributed optimization methods have been widely applied to solve the control and optimization of power systems with a high penetration level of distributed energy resources. Most of the existing distributed control methods can be classified as the following three typical approaches.

The first type of distributed energy management approach is based on dual decomposition. The main idea is to decompose the optimization problem into multiple suboptimization problems, which are coupled by a certain global variable or a uniform Lagrangian multiplier corresponding to the energy balance constraint, such as local marginal price. The control center interacts with all distributed units and also the information exchange among multiple distributed energy units is required to update global information. This type of energy management method does not need the control center to collect all the information from all participants, and the participants can obtain essential and necessary information about the power systems global state. Considering the economic dispatch problem with multiple distributed energy resource units, the objective of minimizing the total cost of power generation should be achieved while satisfying the constraints of power supply and demand balance, the upper and lower bounds of distributed energy resource generation output. Through the dual-decomposition method, the power utility company calculates the global Lagrangian multiplier, and each distributed generation unit solves the local optimization problem and calculates the local output power according to the dual-variable information broadcasted by the power utility company.

Next, a multiple time-scale energy dispatching problem with traditional power generation units, controllable load units, distributed energy storage units, and renewable power generation to minimize the energy transaction cost minus the load utility benefit function is considered. In order to solve this problem, a distributed energy dispatch and demand response algorithm is designed based on the dual-decomposition method and applied to electric vehicle charging scenarios. The cost of traditional power generation is modeled as a quadratic function, a penalty function is imposed to reduce renewable power generation curtailment, and the user preferences are characterized by their willingness to pay for services, which can be seen as benefit functions of users. Users with small energy consumption need to broadcast their aggregated load to the power utility company. The power utility company updates the electricity price based on the deviation of the power generation and load demand. Last, DC-optimal power flow problem considering the upper and lower bounds of generation units power output, transmission line physical limits, power generation, and load demand balance constraints to minimize the total cost of all power generation units is investigated. Each unit updates its power supply or demand and broadcasts it to neighboring units based on the Lagrangian multiplier estimates of the neighboring units' net power. After receiving the transmission line congestion information of the power system, each unit updates the local power supply or demand in an average manner and then updates the Lagrangian multiplier associated with the power supply and demand constraints. The drawback of this type of energy management method is the requirement of a control center. Thus, these are not the fully distributed protocols, and the robustness, privacy protection, and scalability are relatively limited.

The second type of distributed energy management method is based on game theory. The main idea is based on the potential energy game, which can guarantee the existence of Nash equilibrium. Considering a large number of end users cooperate to decide the scheduling of household electrical equipment or load in the next day, power utility company needs to adopt a fixed electricity pricing method to provide guidance for the reasonable energy consumption and proper electricity use time to achieve the Nash equilibrium with the minimum power generation costs. However, this type of approach requires all users to know the power generation cost function information, and the user needs to update the energy schedule asynchronously, so its algorithm is less scalable. Moreover, for the strategy-based potential energy game method, there are special requirements for the network topology, which only apply to fully connected networks, and has no advantage in dealing with complex coupling constraints among units.

The third type of distributed energy management is based on the consensus algorithm, which can achieve global goals through local information exchange. Therefore, this type of distributed energy management has high flexibility, strong robustness, and decent scalability and is fully distributed. As an important branch of distributed computing with minimum communication, consensus algorithms have been widely used in the economic dispatching, demand response, and topology identification problems in smart grids. For the economic scheduling problem of multiple power generation units, the power generation and supply equation constraints are described in the objective function according to the Lagrangian multipliers, and the problem is decomposed into multiple suboptimal problems. Multiple Lagrangian multipliers in the optimal objective function need to converge to the same value, which can be regarded as the optimal marginal cost of the power generation units. Each unit updates the Lagrangian multiplier based on the estimation of the neighboring units' power supply and demand deviation using the consensus algorithm. The updated Lagrangian multiplier is then used to calculate the desired local power generation or load demand.

The distributed energy management methods have the advantages of simplicity, high convergence precision, strong robustness, and decent scalability. Consensus algorithm-based energy management approaches proposed in recent literature are more practical than traditional distributed algorithms. The convergence and the optimality of the consensus algorithm-based energy management methods can be rigorously proved. However, existing consensus algorithm-based energy management methods still have shortcomings in problem modeling, robustness analysis in communication nonideal situations, complex constraints handling, and so on. Therefore, there are still many problems in the consensus algorithm-based energy management methods that are challenging and worth studying.

As a combination of distributed control and artificial intelligence, the multi-agent system (MAS) can decompose large and complex problems into multiple small local problems and realize the local optimal control decision making through the cooperative operations of each agent and other units. Therefore, the MAS is fully applicable to the power systems' collaborative control with well-structured and complex operational objectives because of the following merits: (i) The autonomy of the agent corresponds to the autonomous decision-making ability of the distributed unit in the power systems; (ii) the sociability and teamwork spirit of the agent corresponding to the communication interaction between distributed energy resource units; and (iii) the initiative and adaptability of the agent accommodates the topology change scenario of the power systems with high level of distributed energy resources, such as plug and play, reconfiguration, restoration, etc. As one of the most popular distributed control approaches, a well-designed MAS is flexible, reliable, and less expensive to implement, and it has a better chance of surviving single-point failures. Recently, MAS-based approaches have been applied to various power system applications. However, most of the existing methods are mainly rule-based and lack rigorous stability analysis. The potential applications of MAS for the power grid need to be further explored. Because consensus algorithm can provide the fundamental support, therefore, a MAS-based approaches using consensus algorithm promising have promising applications to address various problems in smart grids with a high penetration level of distributed energy resource units, which is the main focus of this book.