Market-Oriented Operation Pattern of Regional Power Network Integrated With High Penetration Level of Distributed Energy Resources

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Abstract. This paper presents a novel market-oriented operation pattern for regional power grid to meet the demand of market integration at the electricity retail side, especially under the background of high penetration of distributed energy resources accessed. Firstly, the market organizational structure is designed for the proposed market-oriented operation pattern, and characteristics of this operation pattern such as the full marketization and the openness to distributed energy resources are analyzed through the introduction of operation mechanism. Then, an energy management system, which is suitable for the proposed market-oriented operation pattern, is realized by the design of regional network energy management, regional source/load energy management and the effective interaction of these two parts. The energy management processes based on electricity trading plan are proposed. Finally, the main technical problems needs to be addressed are presented. This paper provides a reference for promoting the market integration process of electricity retail side with high penetration of distributed energy resources accessed.

1. Introduction

Awareness to the demands for reducing environmental pollution, achieving sustainable and diverse energy systems and improving energy efficiency, the penetration of new-energy power generation has been growing rapidly in power systems across the world [1, 2]. By the end of 2014, the growth rate of the global new-energy generation capacity had reached 19%, accounting for 6.2% of the total generation capacity. From 2010 to 2011, the EU launched the ambitious “20-20-20” energy strategy for member countries, aiming to increase the share of new energy and renewable energy in energy consumption to 20% by 2020[3]. Meanwhile, the new energy development strategy and action plan of China has proposed that non-fossil fuels and natural gas should account for more than 15% and 10%, respectively, of primary energy consumption in 2020. This paper will cover modular, Distributed Generation (DG) with small capacity, such as renewable energy source-based wind power, solar power and hydropower, and will discuss Distributed Energy Storage (DES) represented by electric cars that operate in the Vehicle-To-Grid(V2G) model. It will also consider Demand Response (DR) program. These topics are collectively known as Distributed Energy Resources (DERs) [4].

At the same time, the liberalization process of the electricity market that is characterized by full competition and complete deregulation also attracts more and more attention. Many countries have initiated market-oriented reforms of power generation and transmission. Currently, marketing the sales side of electricity has become a trend and a popular research topic in power system reformation and development across the world [5]. Central power reformation document No.9 of China intends to
“liberate the sales side of electricity and cultivate major market players through multiple channels”. Currently, more than 30 electricity sales companies have been founded and registered nationwide, and a number of state-owned enterprises are actively preparing for electricity sales. Thus, electricity sales market reformation will be a trend in the future. Considering that most DERs will be accessing low-voltage distribution networks, we selected regional power network (RPN), such as a large city power grid, to study and design the market operation mechanism of its electricity sales.

A comprehensive analysis of these two aspects suggests that a market-oriented operation with high DER penetration is the inevitable new form and requirement faced by future RPN systems. Such DER penetration will bring new challenges and opportunities to its market-oriented operation, as discussed below.

- Novel market-oriented operation pattern of RPN is required to facilitate the integration of DER. Currently, there are two situations standing in the way of marketizing DER access. On the one hand, DER access is facing low status in the market; for instance, setting capacity constraints for market participation [6] prevents DER from participating in the wholesale electricity market competition [7], while excessively high economic penalties for power imbalances [8] discourage DERs from participating in the market. Moreover, technologies that place cutting out DERs as the primary consideration during operation scheduling affect the operational economy of DERs. These challenges are mainly due to power system operation safety considerations, the small capacity of DERs, the random and fluctuating power output of DERs, and the lagging development of DER scheduling and control technology. On the other hand, DER access is also facing high status in the market, for instance, because of excessively high subsidy programs and the requirement for renewable energy to be entirely integrated and consumed, thereby resulting in unilateral, unregulated growth of DER penetration that is separated from the actual electricity utilization scale and from the operation capability of the supply network.

- DER access must be considered in RPN marketization. For example, there are large numbers of DERs with different interest demands and highly distributed ownership/management/control; these represent new conditions that were neither present nor foreseen during the marketization of conventional power grids. Thus, DER-adapted market-oriented operation mechanisms and implementation methods must be designed for RPNs. In contrast, since marketization began, regional grid operators have long been caught in situations in which they can only purchase electricity from external grids; the sales of electricity is liberated while the power sources for purchase are very limited. Therefore, DER access provides a good base and creates conditions that will help to solve this dilemma.

This paper focuses on research into business operation models and the associated implementation programs for marketizing RPNs to meet the needs of RPN market-oriented operation in the context of high DER penetration. First, we analyze the current research on electricity sales marketization with DER access, and then, we propose an operation pattern for RPN marketization based on the above analysis, discussing its organizational structure and operational mechanism. We design an energy management system (EMS) that fits the business model and is not only based on but also achieves organic integration of the regional sources/loads and the regional network energy management; we further propose an energy management procedure based on the electricity trading plan. Phased steps to implement the proposed market-oriented RPN business model are given, and the key technical issues that must be addressed are highlighted.

2. Research Status of Der Access And Electricity Sales Marketization
To eliminate the impacts on the power grid and on users caused by simply integrating into the grid a large number of DERs that are scattered in different locations and have various forms and different characteristics and to improve the market participation of DER and its capability to provide ancillary services, the primary idea is to aggregate multiple DERs into an independent integrated unit in external markets and electricity networks. Currently, the Micro Grid (MG) [9] and Virtual Power Plant (VPP) [10] are recognized to be the most effective way in this domain and have been widely studied.
MGs can work in either the grid-paralleling mode or the island mode through control and coordination [11-13]. Reference [14] used a centralized controller to maximize the benefits of MGs by considering the price of electricity exchange with external grids and the internal energy demand of MGs under capacity constraints for power exchange with external grids and the active power contract between micro-sources and the main controller. Additional related details can be found in [15].

In contrast to MGs, which are more concerned with their own coordination/control and internal economic operation, the concept of VPP has been proposed as a way to improve the economy of DER operation and to help achieve the safe and economical operation of power systems [16]. Based on the functions that a VPP can fulfill, there are two main types of studies on this subject [17]. The first is a Commercial VPP (CVPP), whose basic function is to develop optimal generation schemes based on user-demanded load forecasting and power potential prediction and to participate in market bidding. A Technical VPP (TVPP) ensures that the entire system operates in a safe and optimized way; accounting for physical limitations and the potential services a VPP can provide.

CVPP market operation has bi-level meaning; on the one hand CVPP is regarded as an ordinary participant and competes with other participants in a variety of external markets. Reference [18] analyzed the advantages and disadvantages of the three markets that are accessible to CVPPs, namely, the long-term futures market, the day-ahead market (DAM) and the continuous intraday market (CIM), and noted that uncontrollable DERs fit better in a DAM. Currently, DAM and CIM are most often considered in CVPP studies. The overall time frame and the corresponding operation mechanism of these markets are introduced in [19]. In situation when the total capacity of VPP is considered to be small enough, the VPP is considered to be a price taker and its bid is thus always accepted, and the market price is defined by the other participants [20]. The more popular way is that all market participants including VPPs submit bids and offers with price and MW pairs based on the estimation of its cost, potential income and risk appetite. [21] is concentrated on the participation of a VPP in a joint market of energy and spinning reserve service. A non-equilibrium model is proposed to design the optimization bidding strategy of VPP simultaneously for both markets. An optimal bidding strategy for a CVPP to compete with traditional thermal power plant in the wholesale market was designed based on Nash equilibrium game theory in [22]. A more detailed study and analysis on the bidding strategies of participants in the electricity market can be found in [23].

Currently, VPP scheduling optimization strategies mainly aim to maximize the revenue and to minimize the operation cost of VPP, and they use optimization algorithms to solve for the given output power of each DER by considering equality constraints, such as the active/reactive/power/heating power balance, and inequality constraints, such as the DER output power limit, the limit of the output power change rate, the network line flow limit and the node voltage limit [24]. The benefit/cost calculation for electricity purchase/sale is also typically considered.

To solve the practical scheduling problem that VPP output power may deviate from a previously promised level and thus result in economic penalties, controllable DG, DR and DES are often aggregated into VPPs to reduce the fluctuation and randomness in the output power of VPPs [25]. Another important method to reduce the output power imbalance is phased scheduling. Phased scheduling methods are generally divided into two steps, namely, advance offline planning, which is based on prediction data, and online scheduling, which uses real-time data during operation [26]. Reference [27] employed a two-phase scheduling method to establish an optimized stochastic planning and scheduling scheme that includes new-energy generation and a DR; the scheduling strategy does not require knowledge about the stochastic process probability distribution of the new-energy generation and DR, thus minimizing the mathematical expectation of economic penalties for imbalances.

Studies on the market-oriented operation of electricity sales mainly focus on basic theories, such as the natural monopoly theory, control theory and electricity market theory, on market structure and operational mechanism design [28], and on market participants and power acquisition optimization decisions [29]. Increasing numbers of studies have begun to pay attention to electricity market operations with new-energy generation access [30, 31].

Reference [32] studied the general evaluation and planning framework required by electricity distributors, focusing on DG access. Reference [33] proposed a new system structure and
scheduling/control algorithm that can self-recover when there are multiple MGs accessing the system. The top-level goal is to connect the EMSs of multiple MGs to achieve global optimization and to support the fault area when there is a system error by coordinating multiple MGs. Reference [34] considered both the increased DER penetration in distribution networks and the demands of electricity marketization and designed a double-auction electricity market for a residential area. Reference [35] proposed a two-level decision-making model for distribution companies to participate in the DAM. The model involves two additional energy resources that distribution companies can take advantage of, namely, interruptible loads and distributed generation.

On the whole, current studies on electricity sales marketization have begun to focus on the impact and utilization of DERs; however, there are no effective ways to integrate a large number of scattered small-capacity DERs into the market operation framework. Nonetheless, when using MGs and VPPs to aggregate DERs, most studies have focused on the control and scheduling strategies of VPPs and MGs themselves, and therefore, the methods that are employed are suitable only for specific scenarios and fail to consider VPPs in the context of market-oriented electricity sales.

3. Organizational Structures and Mechanisms of Market-Oriented Operation Pattern

This paper describes the design of a new market-oriented regional power grid (RPN) operation pattern to meet the demands of electricity sales-side marketization with high DER penetration. The organizational structure of the market operation with this model is shown in Fig.1.

![Figure 1. Organizational structure of the market-oriented operation pattern of RPN](image-url)

Primary energy traders that are directly involved in trading with external power markets and are qualified to supply power to the RPN users are located at the first level. In contrast to traditional energy traders, the primary energy traders in this structure are pure interest entities and, under ideal conditions, need not have any ownership in or control of any network, power source, energy storage system, users or information sources. The operating mechanism is to use motivational incentives to dynamically aggregate the large-capacity DGs, centralized energy storage systems, secondary energy traders, and large-capacity users/DRs that are shown in the second level of Fig.1 to form an energy portfolio that participates in trade with external markets and supplies power to users. The number of primary energy traders can be set according to the size of the RPN; access mechanisms similar to the “license” can also be developed, and such licenses may be publicly auctioned to attract the social capital for participation.

The second level primarily consists of a large number of DGs, centralized energy storage systems, secondary electricity traders and large-capacity users/DRs. Each can decide for themselves whether to join the electricity portfolios of one or more primary energy traders through long-term bilateral
contracts. They may choose to do so based on their own situations, their particular objectives or the incentives (mainly price) of programs in the energy portfolio, thereby cutting their costs or increasing their revenues for electricity generation. Specifically, secondary electricity traders can also use business models resembling those of primary traders to aggregate lower-level users/DRs, DESes, DGs or even MGs with motivational incentives to form their own portfolios. Similarly, various entities at the lower level can also dynamically choose for themselves to join one or more of the electricity portfolios of the upper-level traders until all of the DERs and users in the RPN are covered.

In addition, as shown in Fig.1, we also propose the establishment of multiple third-party professional agencies that are adapted to the RPN marketization business model and that focus on handling certain global business interests of the RPN. These third-party agencies are also entities with clear interests.

It is clear that the market-oriented RPN operation pattern shown in Fig.1 will be able to solve the major problems future power grids will face. In terms of marketization, all of the market participants are clearly interest entities that will enhance their revenues and reduce costs and risk of loss through competition. For example, electricity traders at all levels must compete against other traders at the same level in the upper-level electricity market; given that the electricity demands in their own portfolios are met, they can expand their gains by optimizing their participation in the upper-level electricity generation portfolio. Meanwhile, they also compete with other traders at the same level in the lower-level market and motivate interest entities at the lower level to participate in their electricity portfolios by optimizing their price quotes in the lower-level market. In terms of handling access to DERs with high penetration, a market-layering mechanism can be used to expand the size of the energy portfolio created by DER aggregation, thereby improving the opportunities of DERs to participate in market trading, reducing the risk of individual power imbalances, and promoting coordination among the various DERs. Meanwhile, various DERs will be able to independently choose whether to participate in the upper-level energy portfolio plan and to adjust and optimize their operation schemes based on the market, thus motivating capital investment in DERs. Meanwhile, DER investment strategies can also be optimized through market-based mechanisms to assist in making DER investment decisions that are appropriate for the current electricity demand and the grid size; such strategies will also automatically suppress DER penetration beyond its actual level.

Due to space limitations, the following discussion will include only the key components involved in the operation pattern, and only the implementation steps and major technical problems to be solved in this model will be covered.

4. Market-Oriented RPN Energy Management

4.1. EMS Design

The market-oriented RPN EMS is designed to meet the demand for the safe and economical operation of the regional grid and to implement energy management for DERs and users in the context of market-oriented operation. To meet these requirements, the regional grid EMS is divided into two parts in this paper, namely, energy management for the regional network and energy management for the sources/loads in the region. The regional network EMS (NEMS) is responsible for the safe and economical operation of the regional network, and the regional source/load EMS (SLEMS) is designed to achieve market-oriented energy scheduling and control. Meanwhile, the two EMSs can interact and coordinate while controlling the network and its sources and loads, thereby allowing energy management for the entire RPN.

Fig.2 shows the schematic structure of the proposed EMS that is adapted to the market-oriented RPN operation pattern.

A network EMS (NEMS) is based on a dedicated monitoring communication network and can be realized using a network-based control model design [36]. Communication protocols, such as IEC61850 standards [37], can be used to enhance the scalability and compatibility of the system. All of the measuring units used for regional network scheduling and control send the monitoring information to a network information database through the communication network. The network information database integrates processes and stores the information. The regional network operator
can then make energy management-related decisions based on the network information database and can send appropriate control commands through the equipment in the monitoring communications network, thus enacting scheduling and control tasks.

![Figure 2. Schematic diagram of the energy management system architecture](image)

A regional SLEMS uses the Internet as the communications network and is realized by using a fully distributed control model design. Energy traders at all levels and DERs/users all connect to the Internet as clients, where they can conduct a variety of electricity-trading activities on the regional electricity market trading platform and can make their own control decisions, based on market transactions they have completed, to fulfill their scheduling and control tasks. In addition, electricity traders may have direct lines of communication with some of the DERs, shown as a dotted line in Fig.2, that allow them to directly control and schedule these DERs through the ownership protocol for their own needs. Information produced by the SLEMS during energy management is organized and maintained by the SLEMS information database.

The communications between a NEMS and a SLEMS are managed by a NEMS agent that connects to both the Internet and the monitoring information network. This agent is owned, managed and controlled by the NEMS. This arrangement is designed mainly to facilitate compatibility with existing regional EMS and to meet the rigorous security requirements of NEMS systems. A dedicated SLEMS agent can also be set up inside the SLEMS, and the two agents can communicate through a direct communication line (shown as the dotted line connecting the two agents in Fig.2).

Given the above connection, the two EMSes can interact in the following ways. From the viewpoint of the SLEMS, the NEMS can initiate market trading according to its own considerations, such as balancing the market, providing auxiliary services to the market, and restoring market trading for the electricity network; a NEMS can accomplish these tasks using its own market-trading mechanisms. Thus, in this way, the NEMS can be treated as an ordinary electricity trader in the SLEMS. A NEMS can provide the historical/real-time network status information that is required for
making control decisions to various parties trading in the market inside the NEMS; thus, in this way, the NEMS can be treated as a data source in parallel to the SLEMS information database. A NEMS can use its monitoring capabilities over power network equipment to participate in market trades that other electricity traders initiate within the SLEMS, for example, in the highly reliable power supply market; in this way, the NEMS can be treated as a special DER. A more important possible function of a NEMS is to approve the trading plans of the market and to monitor/schedule the implementation of energy management in the SLEMS in the context of the safe and economical operation of the RPN; in this way, the NEMS can be treated as a special supervisor of the SLEMS.

Within a NEMS, a SLEMS can likewise be considered as a special monitoring information source and a controllable scheduling resource. Users and DERs within the SLEMS all have local monitoring capabilities, and historical/real-time monitoring information can be transmitted to the NEMS and serve as a source of supplemental information or of backup/verification data. A market-oriented business model typically does not implement programs that use a NEMS to directly control loads/sources within the SLEMS; instead, indirect source/load scheduling and control are achieved by initiating the corresponding market trading within the SLEMS.

4.2. Energy Management Implementation

The regional grid energy management process in the market-oriented operation pattern can be initiated by different objects at different management phases and with different management objectives. In this paper, the regional grid energy management process is designed to use the electricity trading plan as the carrier. The energy management process that is based on the electricity trading plan is shown in Fig.3.

![Energy management process diagram](image)

**Figure 3.** Energy management process based on transaction plan

The energy management process is divided into 3 phases, namely, advance planning, real-time scheduling and post-processing.

The advance-planning phase of energy management can be further divided into phases such as transaction initiating, transaction forming and transaction approving, according to the status of the
electricity trading plan. Typically, the energy management process is triggered by a trader at any level sending out an energy trading plan. By using data such as historical trading information in their local database and the SLEMS database, in addition to historical/real-time network operation information in the NEMS database, traders at all levels can autonomously make control decisions and release electricity portfolio purchase plans on the regional market trading platform. The plan contents can vary depending on the market involved. For example, for long-term contract markets, a plan may include the contract period, the electricity, and the price of the contract and default clauses; for a DAM, the plan may include pricing for phased electricity and the imbalance penalty. Capacity limits may be set to prevent entities that do not meet the conditions from participating, and different prices can be set according to the capacity levels and lengths of participation to attract high-quality entities to participate in the released electricity purchase portfolio plan as soon as possible. Traders at all levels will also release electricity sale portfolio plans, which may include electricity sales plans in the form of long-term contracts for large-capacity users and short-term electricity sales plans for small-capacity users. In addition, different prices can be set for electricity sales plans with different reliability levels to achieve the objective of high price for high quality.

In the formation phase of a transaction, given that the limiting conditions set by the plan are met, users and DERs, or even energy traders at all levels, may participate in the trading plan and choose to join a certain plan in the regional market trading platform based on historical information in their local database, the electricity purchase portfolio, or the electricity sales portfolio plan. The program selection decisions typically aim to maximize gains, and they are based on the available data and capability of a participant. For large-capacity users and DERs, their local EMSes can implement the decision-making process.

The plan sponsors can conduct real-time tracking and assessment of the implementation of the trading plan that they initiated. Without prejudice to the interests of the plan participants, they can modify the trading plan to maximize the expected benefits and to achieve early implementation of the trading plan. Participants in the plan can also perform real-time tracking and evaluation on other existing trading plans or opt-out of their current plan and join another trading plan. Through the process described above, various trading plans will eventually be implemented, and those that cannot be implemented will be withdrawn or re-launched.

At the trading plan approval phase, the power grid operator can comprehend the various electricity purchase and sales portfolio plans that have been implemented, together with the power supply status of the RPN, to evaluate and predict the operation of the network. They can also approve trading plans that meet the network operation requirements and develop appropriate plans that adjust the network to ensure that the approved trading plans can be successfully implemented; for trading plans that do not meet the requirements for network operation, they can ask the trading plan sponsor to modify the plan, noting for the plan sponsor’s reference conflicts such as time, location, and the amount of power. For plans that meet the operational requirements but do not permit the economical operation of the network, they can induce the traders to modify their plans by means such as adjusting the fees for using the regional network. Once approved, a trading plan can enter the actual implementation phase.

The real-time scheduling phase of energy management mainly refers to the actual implementation of the trading plan. The EMSes of DERs and users can make independent decisions, based on the trading plans in which they participate, about how to control DERs and electrical equipment to optimize their own energy management while ensuring that their electricity in the network is compliant with the requirements of the trading plans so as to reduce the financial penalties caused by discrepancies with the trading plan. In the actual scheduling process, real-time measurements of local power will also be sent to the trading plan initiators to serve as evidence of transaction completion. After receiving real-time measurements from various plan participants, the plan initiator will also make real-time scheduling and control decisions using their own data, thereby reducing the discrepancy between the actual scheduled power and the power promised in the trading plan and avoiding the corresponding financial penalties.

The roles and tasks of a RPN operator at the real-time scheduling phase of energy management are to control and schedule the grid equipment to ensure the safe and economical operation of the RPN. The coordination of the sources and loads in the RPN needed to reach the scheduling and control
targets can be achieved by initiating within the market appropriate trading plans, such as active power imbalances, reactive power and voltage regulation, and power quality regulation. In an emergency situation, when the safe and stable operation of the RPN is threatened, any measure or approach may be taken to ensure the safe operation of the power grid.

The post-processing phase of energy management mainly involves third-party fund settlements and profit distribution based on the actual implementation of the trading plan and the advance agreements. Disputes that arise during this process are handled by a third party, together with the various parties involved. The trading is completed after all of the related matters are processed, and the energy management process also ends at that point. The various trading parties will process all of the information involved in the trade to generate historical data that will support subsequent trades they will initiate or in which they will participate.

The above-described EMS and energy management process will have the features and advantages discussed below.

It will be adapted to the requirements of a market-oriented RPN business model: the parties involved in the energy management process are entities with clear responsibilities and rights, and the entire energy management process is realized in a market-oriented manner. It will meet the requirements for high DER penetration: through market-oriented operation, the DER penetration level will eventually adapt to the consumption level and to the network operation capability, and it will also induce the growth of electricity consumption and network operation capabilities, thereby resulting in the dynamic and coordinated development of the three. The operations and interactions of NEMS and SLEMS can ensure both the economy and safety of the RPN operation, as they are highly compatible and scalable: by accessing the unified regional market trading platform through the Internet, both DERs and users can immediately participate in the energy management process. The EMS is characterized by completely distributed and intelligent control: the control decisions of electricity traders, DERs, and users are made based on their own intelligence, without any centralized control. The EMS will achieve simultaneous competition and collaboration among individuals: electricity traders, DERs and users aim to maximize their own interests when participating in the market competition, while also collaborating to implement the global trading plans initiated by the regional network operator.

5. Conclusions

In this paper, a market-oriented RPN operation pattern and its EMS are designed and studied in the context of high DER penetration. The operation pattern can accommodate the requirements for both RPN marketization and DER access, and it has the advantage and characteristics of a high degree of compatibility and scalability, fully distributed intelligent control, and organic integration of individual competition and coordination. We intend for this study to be a useful reference for promoting electricity sales-side marketization when DERs are integrated into the operation.

Due to space limitations, the macroscopic problems (e.g., national policy and the establishment of regulations and laws) and technical problems (e.g., trading platform construction, interest entities’ pricing mechanisms, and communication and information platform construction) involved in the implementation of the market-oriented RPN business model are not discussed in this paper. These issues must be solved and improved in subsequent studies. Meanwhile, in the proposed business model framework, it is clear that by organically integrating innovative ideas from other industries and effectively combining the latest technologies, such as Internet connectivity and big-data analysis, additional new service and business models can be created. For instance, funds or equipment may be provided to users to build distributed power generation units, and prepaid electricity fees may be pooled to allow participation in trading in the financial markets. All of these topics warrant further in-depth study.

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