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Smart Grids to Revolutionize Chinese Cities

AS SMART CITIES STRIVE TOWARD using green and renewable energy, sustainable energy plays a critical role. A smart city requires its energy generation, supply, transmission, distribution, and management components to be modular, automated, reliable, safe, and controllable. A smart city energy system must be reliable, efficient, and robust against attacks. It must have adequate supply availability and redundancy. These are key characteristics of a practical and useful energy system.

Smart cities employ technology and data to increase efficiencies, economic development, sustainability, and life quality for citizens in urban areas. The sensor data are used for in-depth study of systems to determine the susceptibility of failure, critical situations, and restoration schemes by adding renewable energy resources. An analysis framework will be used to study the impact of emerging trends in power grid operation. The framework may also be used to develop contingency plans to optimize the generation, transmission, and distribution schemes, thus providing more flexible solutions. The proposed framework may also be used to enhance the security features of

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Challenges and Opportunities

a supervisory control and data acquisition (SCADA) system, which leads to significant improvements in energy efficiency and the secure use of renewable energy.

A city management's ability to provide security, sustainability, and a high standard of living for its citizens is important. This is the main aim of a smart city. The concern about increased greenhouse gas emissions, resulting in revised laws and regulations, leads to the need for sustainable and clean energy to reduce energy demand and improve energy efficiency. A radical restructuring of the energy supply is underway to ensure sustainable prosperity and minimize blackouts. This transformation includes the introduction of new elements at all levels in the chain of production, delivery, and use. It involves new network configurations, design and operational procedures, incentives and business models, social structures, and policies.

The authors investigate three real-life projects on smart energy and how they could improve the quality of life in those cities. The article also discusses potential challenges and opportunities based on the experience from these projects.

Project 1: A Multienergy and Battery Complementary Control System

To provide clean energy in contribution to the smart city vision, this project commissioned a complementary control system for 400-MW wind power, 200-MW solar photovoltaic (PV) power, 50-MW solar thermal power, and 50-MW battery storage. The project is in Golmud City, Qinghai Province, China. The system coordinates wind, PV, and solar thermal power and batteries to improve the renewable energy penetration level and strengthen power system security.

Power system operation flexibility is improved by scheduling and controlling these resources and taking advantage of their different, complementary space and time properties. The control center communicates with various power plants by using SCADA in the demonstration area. The instructions issued by the provincial grid automatic control system were analyzed, and the real-time control of the subordinate wind farm, PV solar farm, solar thermal plant and battery storage station was realized. The operation status, interaction status with other systems, statistical evaluation, and other information of the multienergy complementary system were sent to the big data platform of the centralized control center.

The Overall System Architecture

Wind, PV, solar thermal, and battery complementary control systems consist of monitoring, information acquisition, decision support and control, and instruction-issued modules. The proposed control system receives the total instruction, day-ahead, and intraday scheduling plan from the provincial grid automation system to optimize operation of each power plant. It also sends real-time instruction to wind farms, solar PV farms, and solar thermal and battery storage stations. The system interface is shown in Figure 1.

Interface and Information Interaction

The multienergy complementary and coordinated control system can exchange information with wind farms and with PV, energy storage, and solar thermal power stations. This exchange is achieved by communicating with the on-site monitoring system, substation integrated automation system, and active support system.

The instructions issued by the provincial automation system were decomposed, and the real-time control of the lower-level wind–solar thermal storage power station was realized through the active support system. The operation status of the multienergy complementary system, the interaction status with other systems, and the statistical assessment information were sent to the centralized control center of the provincial data platform for data storage and analytics.

The Hardware Structure

The multipower system hardware platform consists mainly of servers, data storage, workstations, and network switches. The servers all have dual-system redundant standby mechanisms, including a database server, data acquisition server, monitoring server, decision computing server, and control server. Network switches include two trunk switches, four collection switches (dual plane), and two man–machine switches. Figure 2 illustrates the detailed hardware configuration.

Alarm Monitoring

The multienergy control system integrates measured information from real-time system operating statuses, such as wind power, solar power, energy storage state of charge, and solar thermal power. Using data preprocessing techniques (e.g., data validation and error correction), the real-time data are derived for the multienergy control system. In the visual display platform, techniques, such as coloring, status prompt, dynamic data, and multilevel classification, were applied to show the real-time generation output power of each power plant. Command, prediction output comparison, bus voltage level, energy storage equipment operating status, and charge and discharge times of the battery will also be shown.

Decision Support Function Design

The decision support function detects the scheduling plan (day ahead and intraday) and real-time instruction information delivered periodically by the provincial commission.

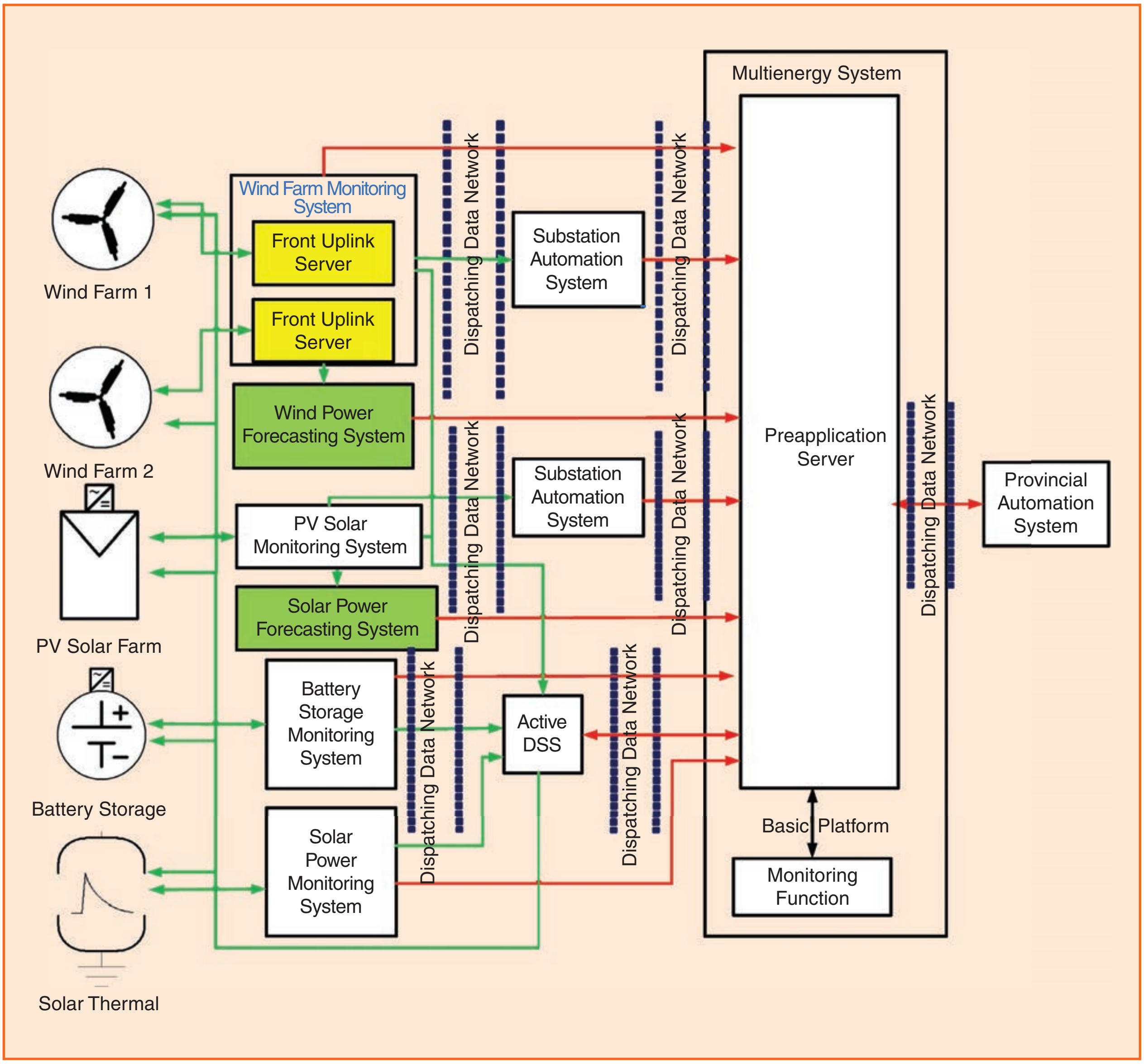

figure 1. The system interface diagram. DSS: decision support system.

If the scheduling plan and real-time instruction update are detected, the corresponding decision calculation is started.

From a time point of view, decision support is divided into three stages: day ahead, intraday, and real time. The day-ahead part focuses on the long period optimization of solar thermal, storage deep charge, and deep discharge plan. For intraday scheduling, based on the day-ahead plan, there is a need to have step-by-step rolling deviation corrections. In the real-time plan, based on intraday, the real-time instruction and generating capability must be calculated. The real-time allocation of real power is accomplished by sending instructions to the wind, solar, solar thermal, and battery storage stations.

Day-Ahead and Intraday Optimizing Decisions

The day-ahead optimization decision is based on the day-ahead plan target value and short-term forecast issued by the provincial automation system. The goal is to minimize the comprehensive deviation between the day-ahead plan and the target value. The weighted coefficient reflects the price, prediction accuracy, and control performance. Priority will be given to the power plants with higher electricity prices and better prediction accuracy and control performance.

For decision making, the number of battery storage deep charging and discharging times is considered. The long-period charging and discharging planning of energy storage is optimized by taking the global perspective of the minimum deviation of the whole period into account. Coincidently, the day-ahead planning of each power plant is optimized in each period considering the security constraints of the power grid and other operation constraints of the power generation equipment.

Similar to the day-ahead decision support, the intraday optimization decision is based on the provincial intraday plan and ultrashort-term forecast. The goal is to minimize the comprehensive weighted deviation between the intraday plan and the target value.

Real-Time Optimization Decision

The real-time optimization decision is based on the real-time generation capability and real-time control instruction issued by the provincial dispatch and control center. The issued power plant instructions are generated by rolling optimization from day ahead to real time.

Real-Time Control Function

According to the relationship with the provincial control center, two control modes—provincial direct control and local control—are designed for the multienergy complementary control system. In provincial direct control mode, the control instructions of wind farms, solar PV power stations, and solar thermal power stations are calculated by the provincial dispatch and control center and issued to the power plants directly. In local control mode, the provincial regulation issues only the target value of active power and voltage on the side of the 330-kV tie line, and the system further decomposes and issues the control instructions for wind

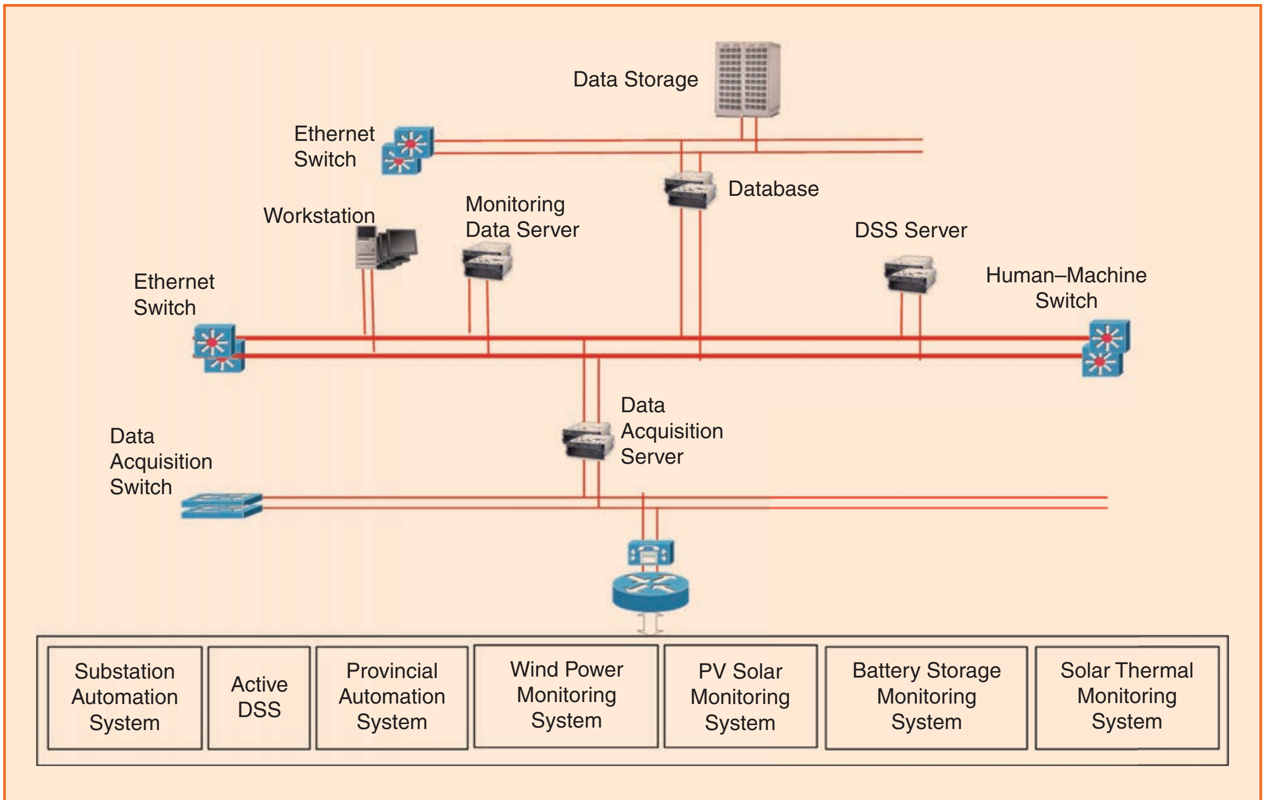

figure 2. The system hardware deployment.

> The proposed control system receives the total instruction, day-ahead, and intraday scheduling plan from the provincial grid automation system to optimize operation of each power plant.

farms, solar PV power stations, energy storage systems, and solar thermal power plants.

The multienergy control system (Figure 3) communicates with the provincial control center through the dispatching data network. The system receives the information delivered by the provincial dispatch and control center. This includes the control mode flag bit of the multifunctional system and the control instructions. The control mode flag bit is responsible for the multienergy system determining whether to adopt the provincial direct control mode strategy or the local control mode strategy.

In the local control mode, the provincial control center only issues the power target value at the gathering station side of the 330-kV Luwang line. Only the output of the whole plant is controlled. At this time, the multienergy system further carries out the coordinated optimization control of wind–PV–solar thermal–battery storage. It calculates and sends the control target of each control object to the active support system, which then forwards it to the centralized control system of each control object. To ensure the reliable operation of the multienergy complementary system, the control subsystem module adopts an independent configuration and independent operation mode for instruction checking and delivery.

The system can set three control modes: the time-driven, event-driven, and manual modes. The control subsystem detects the instruction by receiving a mark from the decision subsystem in seconds. During normal operation, the system adopts the time-driven mode, which means a fixed cycle mode. The decision subsystem of the system generates a control instruction every 30 s, and the control subsystem sends it synchronously. When the system detects abnormal events and unsafe states, such as line overloading and bus overvoltage, the system automatically speeds up the calculation and control period to 10 s. The system provides a manual trigger control interface. For instance, if the system is under maintenance, the operator can manually add or delete a single wind turbine or solar panel, modify calculation parameters, or batch process for the wind turbines and solar panels under control.

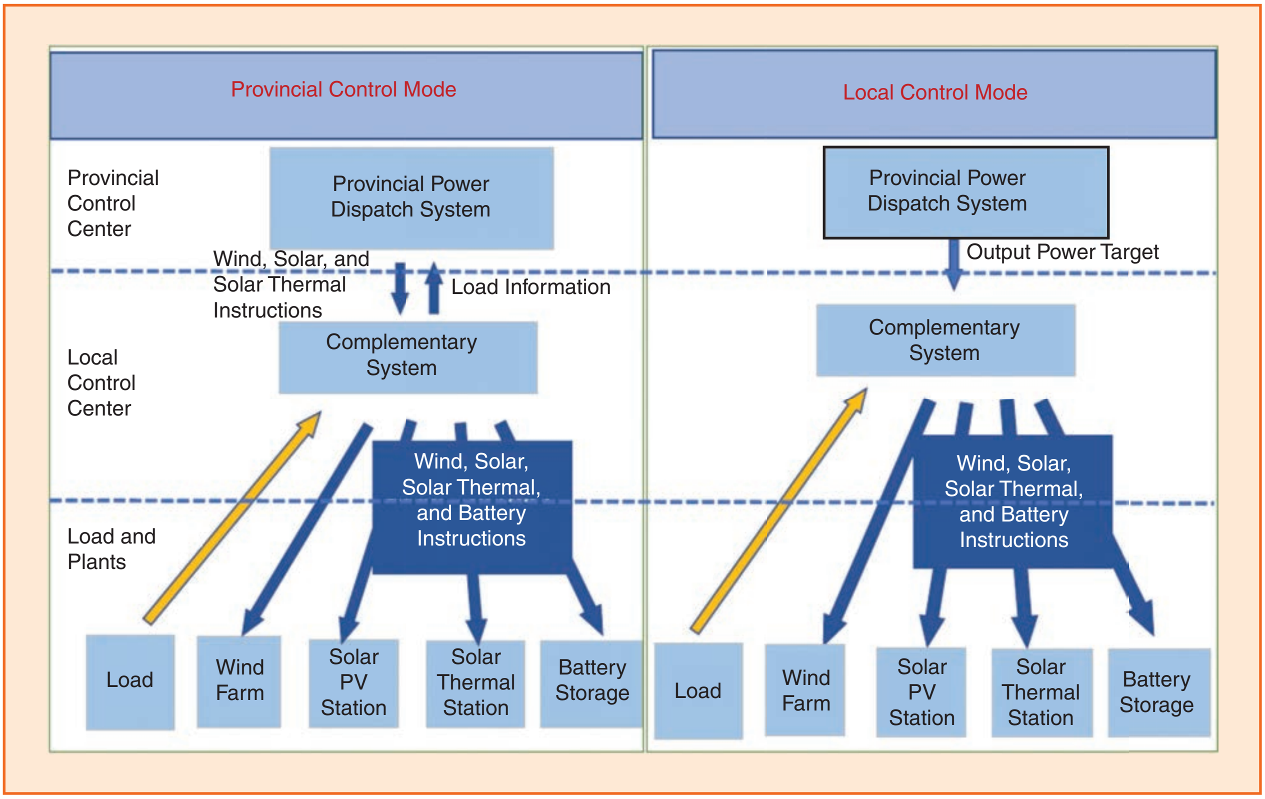

figure 3. The multienergy complementary and coordinated control system.

The system can check the control instructions given by the decision mode and identify abnormal instructions. Once in abnormal condition, the system can switch the instruction source automatically and read the new control instruction. If all control commands are abnormal, the lock command will be sent to the system, and an alarm is pushed actively.

The demonstration systems can complement each other to improve the renewable energy consumption level. By taking advantage of different energy resources' complementary properties of space and time, the system improves the operational flexibility of the power system. The renewable energy consumption level is increased by coordinated scheduling and control of the multienergy resources.

Compared with traditional renewable energy sources, this project combined PV, solar thermal, and wind power as developed power sources. Solar thermal energy storage systems and battery energy storage stations are applied as regulated power sources. A variety of power settings can effectively solve the problems of uncertainty and variability of wind power and PV power and the imbalance problems of power output during peak and off-peak periods. An example of the effect of complementary control on power curtailment is given in Figure 4.

The project was in operation starting in January 2019. This demonstration explores the benefits of a renewable energy power station to actively participate in grid frequency and voltage regulation. When the frequency and voltage of the grid fluctuate abnormally, the power station in the demonstration area can quickly participate in the dynamic support of active power-frequency and reactive power-voltage of the grid. This dynamic support influences the security and stability of grid operation.

The project's frequency adaptive adjustment range is 48–50.5 Hz, and the voltage is 0.9–1.1 p.u. The steady reactive voltage control response time is ≤ 3 s, while the transient reactive voltage control response time is ≤ 100 ms. The primary frequency modulation start time is ≤ 1 s; the response time and regulation time are ≤ 5 s and ≤ 10 s, respectively. The inertia response time is ≤ 200 ms, and the active power regulation control error is ≤ ±2% PN.

This system realizes a real-time absorption capacity to respond to fluctuations with a rapid evaluation calculation time ≤ 1 min, a multienergy complementary coordination calculation time ≤ 30 s, a control deviation ≤ 2%, and an annual wind and solar curtailment rate ≤ 5%. The annual power generation is about 1.26 billion kWh, that is, with a savings of about 0.4 million tons of standard coal every year, which will effectively reduce coal consumption and greenhouse gas emissions.

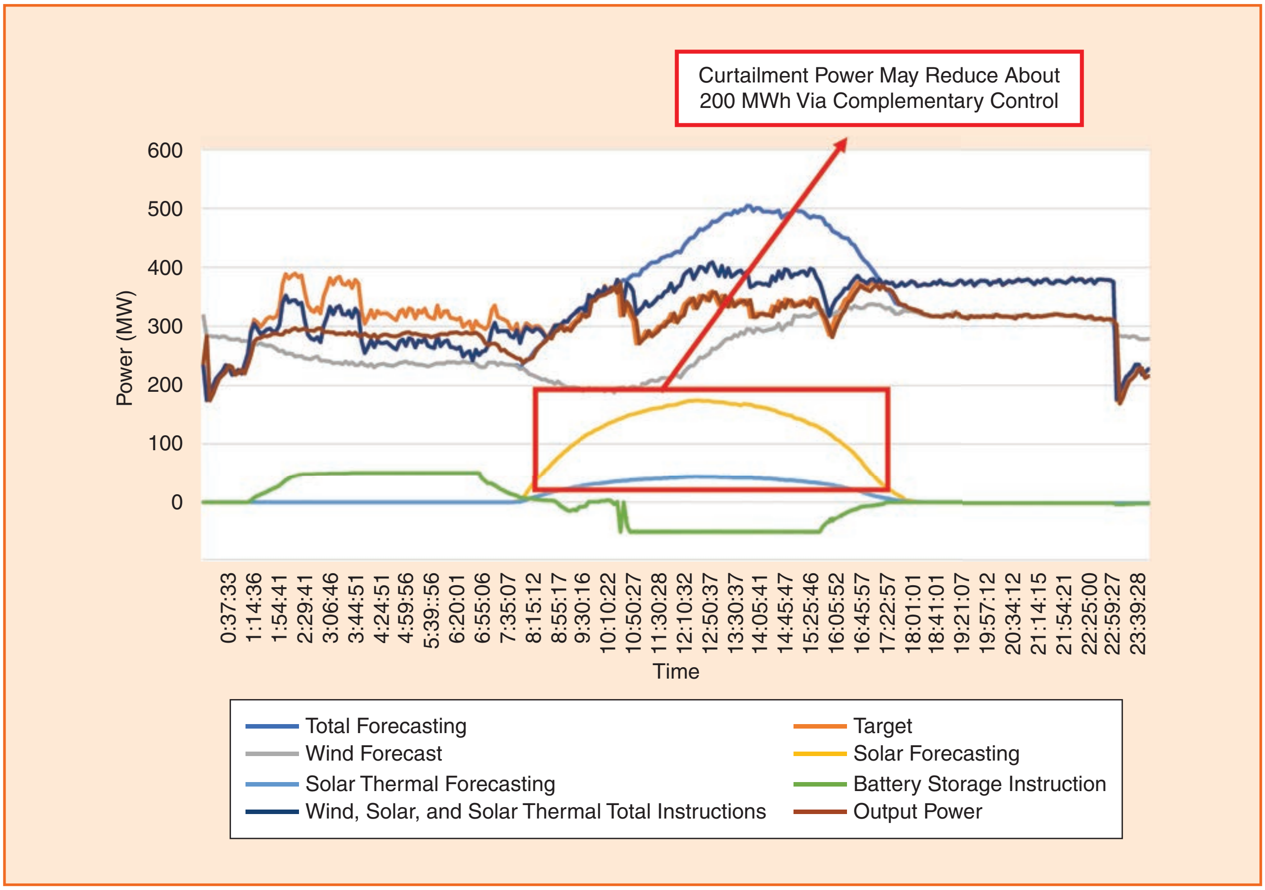

figure 4. An example of the effect of complementary control on curtailment power.

> Similar to the day-ahead decision support, the intraday optimization decision is based on the provincial intraday plan and ultrashort-term forecast.

Project 2: AC/DC Hybrid Distributed Renewable Energy System

The second project is based in Tongli Town, Suzhou, Jiangsu Province, China. Suzhou Tongli is a "renewable town" approved by the National Energy Administration, China. This project is a new energy demonstration built by State Grid Corporation and the Jiangsu provincial government. The Suzhou municipal government is actively building a "green Tongli" model of energy development.

It is an ac/dc hybrid distributed renewable energy system. The application of a multifunction power electronic transformer made it possible to build a flexible and open ac/dc hybrid network topology. The project also integrated an ac/dc power supply and flexible plug-in loads, developed an ac/dc power supply system (with a dc supply–dc load and an ac supply–ac load), and reduced the energy conversion losses to improve the overall energy efficiency.

Power grid operation and control are becoming more complex with increased wind power, solar PV power generation, solar thermal, battery storage, and other forms of distributed generation (DG). Power electronic transformers can effectively support the integration of all kinds of distributed energy resources. For microgrids, they can support operation in islanding mode. They can easily switch to grid-integration mode to improve power quality and power supply reliability. To ensure the safe and reliable operation of an ac/dc hybrid renewable energy system, distributed power supplies, energy storage equipment, and interconnected converters have to adopt reasonable and effective control strategies. These strategies need to adhere to the power grid structure and operation control modes.

The Tongli demonstration project uses a four-port power electronics transformer to build an ac/dc hybrid system that can realize flexible networking and integrate distributed renewable energy at multiple ac/dc voltage levels to achieve flexible and secure access. The system can also reduce the energy conversion link to minimize power loss. It improves energy utilization efficiency and enhances the system control ability in a wider range of interconnection. The ac/dc hybrid distributed renewable energy complementary optimization operation control system includes five functional modules: real-time monitoring, coordinated control, short-term scheduling, analysis and evaluation, and operation simulation.

Real-time monitoring includes mainly real-time data and curve monitoring of wind, solar PV, battery storage, and photothermal power, the power conversion system inverter, electric vehicle charging pile, load, and power electronics transformer as well as comprehensive display and monitoring. The coordinated control strategy includes dispatch instruction tracking, local control, ac/dc smooth switching, and dc voltage control. Short-term scheduling includes optimization mode selection and renewable energy consumption evaluation. The optimization mode includes the islanding operation mode, minimum power curtailment operation mode, and economic operation mode. The analysis and evaluation module includes generation analysis, voltage analysis, availability analysis, and fault analysis. Generation analysis and voltage analysis include daily analysis, monthly analysis, and annual analysis for statistics.

This project was commissioned in October 2018. It resolved the problems of coordination among multiple types of power electronics flexible equipment and the existing control and protection system as well as the information exchange between ac/dc key equipment (e.g., power electronic transformers and fault current controllers) and the operation control system. To examine the system structure, source characteristics, equipment performance, and operation control strategy, a modular integrated test verification platform was built. This was based on ac/dc hybrid distributed renewable energy systems.

Fault current controllers are intelligent electrical devices developed through modern power electronics technology and material engineering. A fault current controller is connected in series in an ac/dc network to limit the circuit fault current so that the power grid equipment can avoid damage due to significant overcurrent situations. Figure 5 shows the integration of functional components of the ac/dc hybrid distributed renewable energy system.

The project consists of five components: system design, optimal configuration and energy efficiency assessment, key equipment development, complementary optimal operation control, and system integration and demonstration. The system design box generates typical topologies of ac/dc hybrid systems and provides an analysis of the dynamic characteristics of the ac/dc hybrid system optimal configuration. The energy efficiency assessment box contributes the operation boundary for the complementary optimal operation control box. The key equipment development and complementary optimal operation control boxes provide hardware and software for ac/dc hybrid distributed renewable energy system integration and demonstration.

Technically, the control functionality of the ac/dc hybrid distributed renewable energy system was developed in Java and C languages. The realized software architecture optimization was based on the platform of the Smart Grid Dispatch and Control Technology Support System. The modular design ensures the stability and robustness of the system. The system provides a friendly man–machine interface with high reliability, scalability, and maintainability.

The maximum penetration rate of renewable energy in the demonstration area can be increased from 30 to 40%, effectively replacing the coal consumption of conventional coal-fired power plants in Suzhou. The annual replacement coal consumption is about 110 million tons, and the annual reduction of carbon dioxide emissions is about 250,000 tons.

By optimizing the power supply modes of the dc supply–dc load and ac supply–ac load, the energy exchange between the ac and dc systems is reduced, which improves the power supply efficiency. The construction of a dc low-voltage distribution system minimizes the number of distribution lines required and reduces the line power losses, thus attaining an annual electricity savings of about 500 MWh. The power supply capability of multiple power electronics transformers is used to realize the transfer of important loads and improve the reliability of the power supply in the demonstration area.

The power electronics transformer functions, such as electrical isolation, reactive power compensation, and active filtering, are used to effectively suppress the influence of fluctuating power supply on power quality and improve the power supply quality in the demonstration area. The annual power loss and power quality economic loss of power users can be reduced by about 3 million RMB (China's currency), which equals US$0.43 million.

Project 3: Power Restoration Control Decision Support System

The third project is based in Qingdao, Shandong Province, China. The power restoration control decision support system combines regional power grid information and a communication network. The system can restore the power supply in time to avert extreme disaster situations while considering security and economic efficiency. A power supply for important loads of the regional power grid is guaranteed. The reliability of the regional power grid is improved, and the minute-level auxiliary decision of power grid online restoration control has been realized. The preferred recovery plan can be achieved according to the power outage load recovery priority results, an online search for recovery alternatives with the

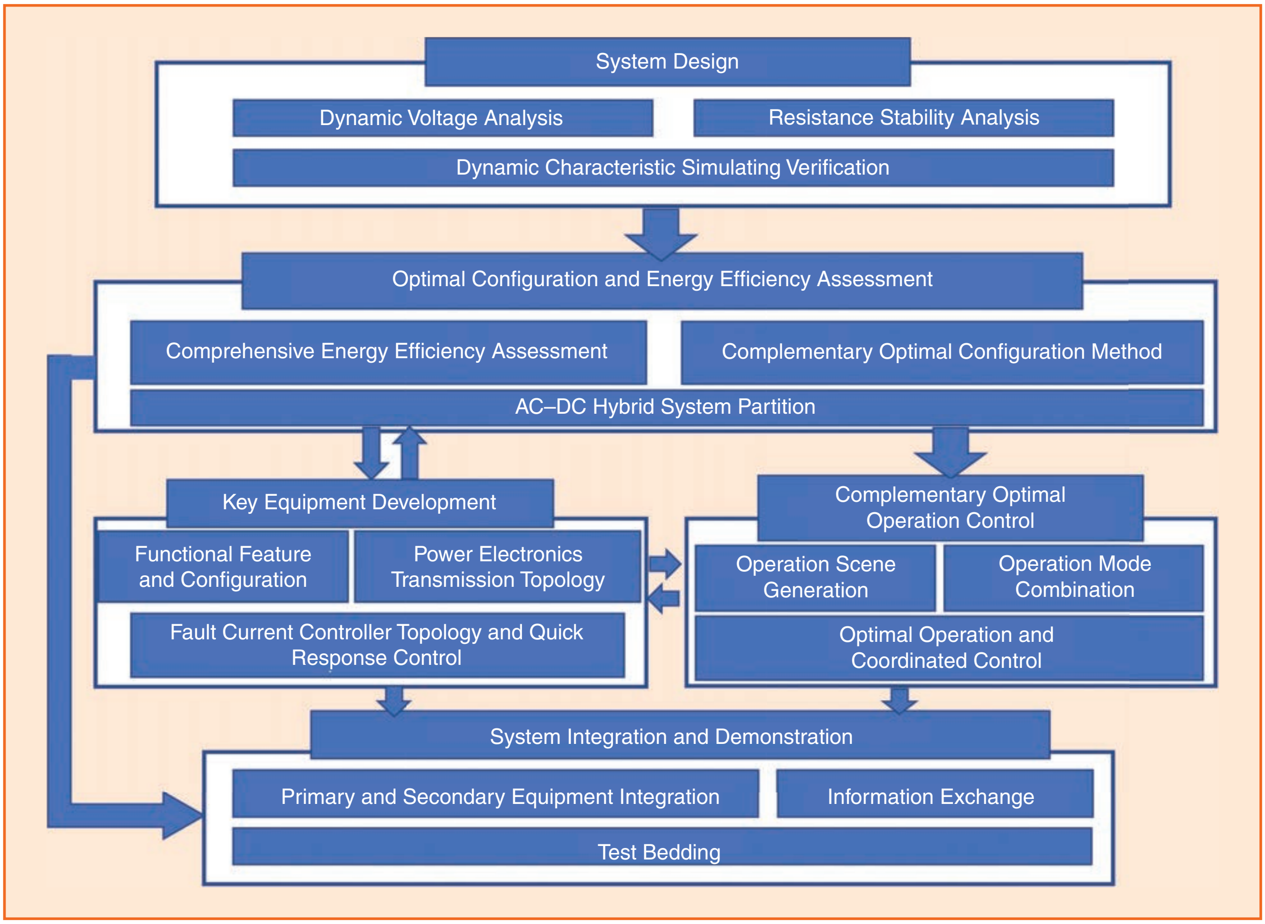

figure 5. The integration of functional components of the ac/dc hybrid distributed renewable energy system.

> The annual power loss and power quality economic loss of power users can be reduced by about 3 million RMB (China's currency), which equals US$0.43 million.

maximum recovery load per unit time, and power system security check options.

The overall architecture of the system (Figure 6) is based on the premise of security protection. This architecture establishes cooperation between the internal and external networks and promotes the optimization and integration of the business at all levels. The internal network consists of a SCADA system, a power network, and an information communication network. The external network consists of a transportation network.

Application Architecture

Based on an Internet of Things (IoT)-inspired connectivity among smart devices and a power system-integrated network, the decision-making support system (Figure 7) is composed mainly of three modules: 1) the network monitoring module, 2) the emergency repairing module, and 3) the real-time restoration control module. The detailed application architecture is described as follows.

Data Input

To make cities operate affordably and sustainably requires the deployment of more sophisticated control and management systems. The efficiency, availability, reliability, and sustainability of clean electric energy are critical for citizens.

The real-time system must synchronize with underlying physical and service data through the integration of multiple data sources. A holographic sensing system is based on the mining and analysis of basic data. It provides clients with a service interface to call for the analysis results. The client uses the analysis results in operator displays and management functions. The client may share or push relevant information to third parties so they may have effective and timely notification of relevant information.

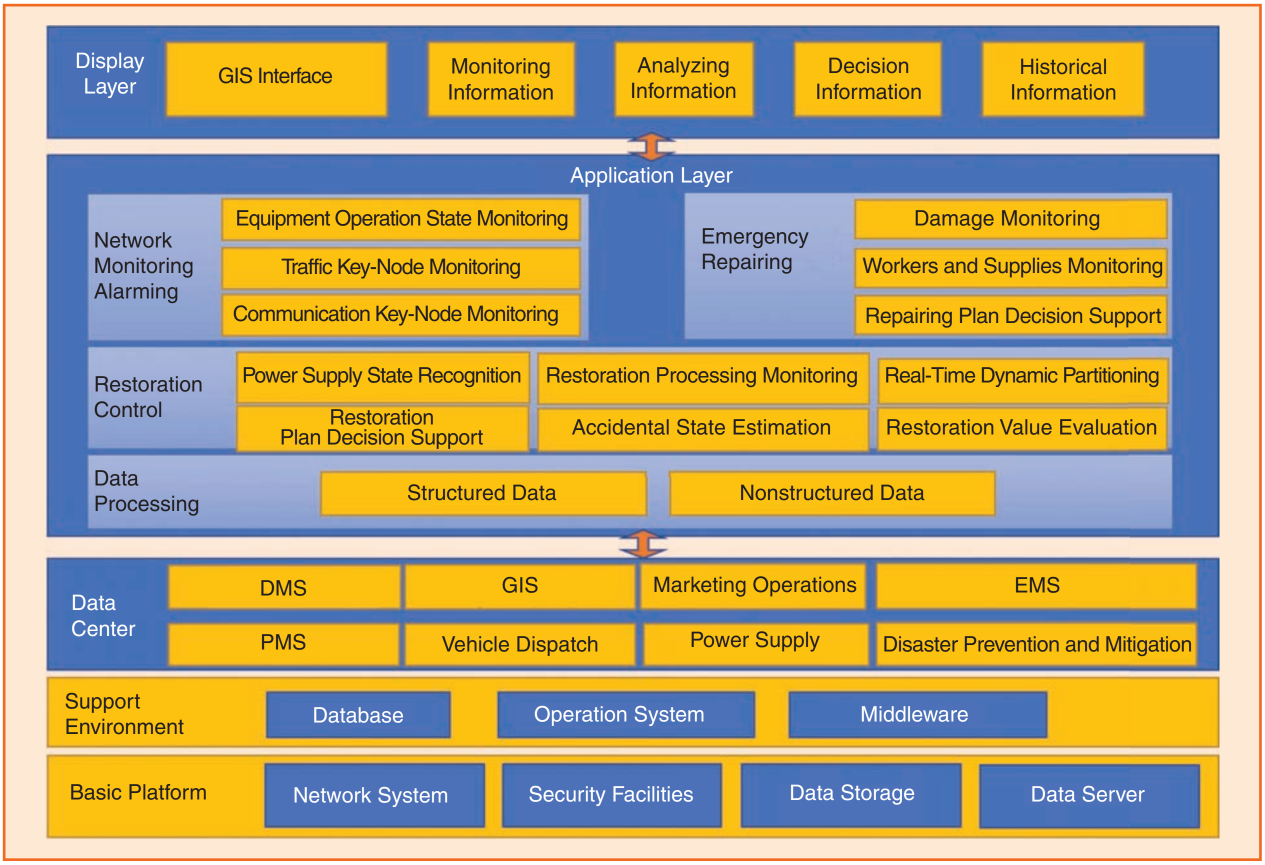

figure 6. The overall power restoration control decision support system structure. EMS: energy management system; DMS: distribution management system; GIS: geographic information system; PMS: purchase management system.

The system consists mainly of the following subsystems:

- ✔ *SCADA system*: to monitor and control the power plants
- ✔ *distribution management system (DMS)*: a group of applications developed to monitor and control the entire distribution network reliably and efficiently
- ✔ *energy management system (EMS)*: a system of computer-aided tools employed by electric utility grid operators to monitor, control, and optimize the generation or transmission system's performance
- ✔ *purchase management system (PMS)*: a system that develops customized approval rules providing the ability to hasten approvals and order placement for the timely receipt of power system equipment (e.g., a relay).

Network Monitoring Module

As shown in Figure 7, the network monitoring module consists of the following functions.

Equipment Operation State Monitoring

The system monitors the operating status and related electrical parameters of the power equipment within the scope of the dispatching mechanism. The system can also collect the meteorological and disaster information where the power equipment is located. According to the power grid state estimation data and equipment maintenance plan, operators can judge the power equipment (e.g., the generator, transformer, and transmission line) operation status and distinguish the unplanned outage and planned outage equipment.

Traffic Key-Node Monitoring

The connection status of key communication network nodes in the current power grid is obtained and monitored by calling the external interface. Operators can specify the communication network nodes to be recovered and obtain the recovery status of key network nodes by calling the external interface.

Communication Key-Node Monitoring

By calling the interface provided by the external system, the status of the starting and ending points of the critical traffic path collection of the power grid is obtained for monitoring. Given the latitude and longitude of the starting point and the endpoint, the external system interface is called to obtain the fastest and most reliable paths and their estimated times.

Emergency Repairing Module

As also shown in Figure 7, the emergency repairing module consists of the following functions.

Damage Level Monitoring

This function provides various types of disaster damage statistical information, major load damage statistical information, and transmission channels related to major damage load statistical information. With a typhoon, for instance, disaster damage could include broken poles, tilted poles, broken lines, flooded station rooms, and flooded ring network cabinets.

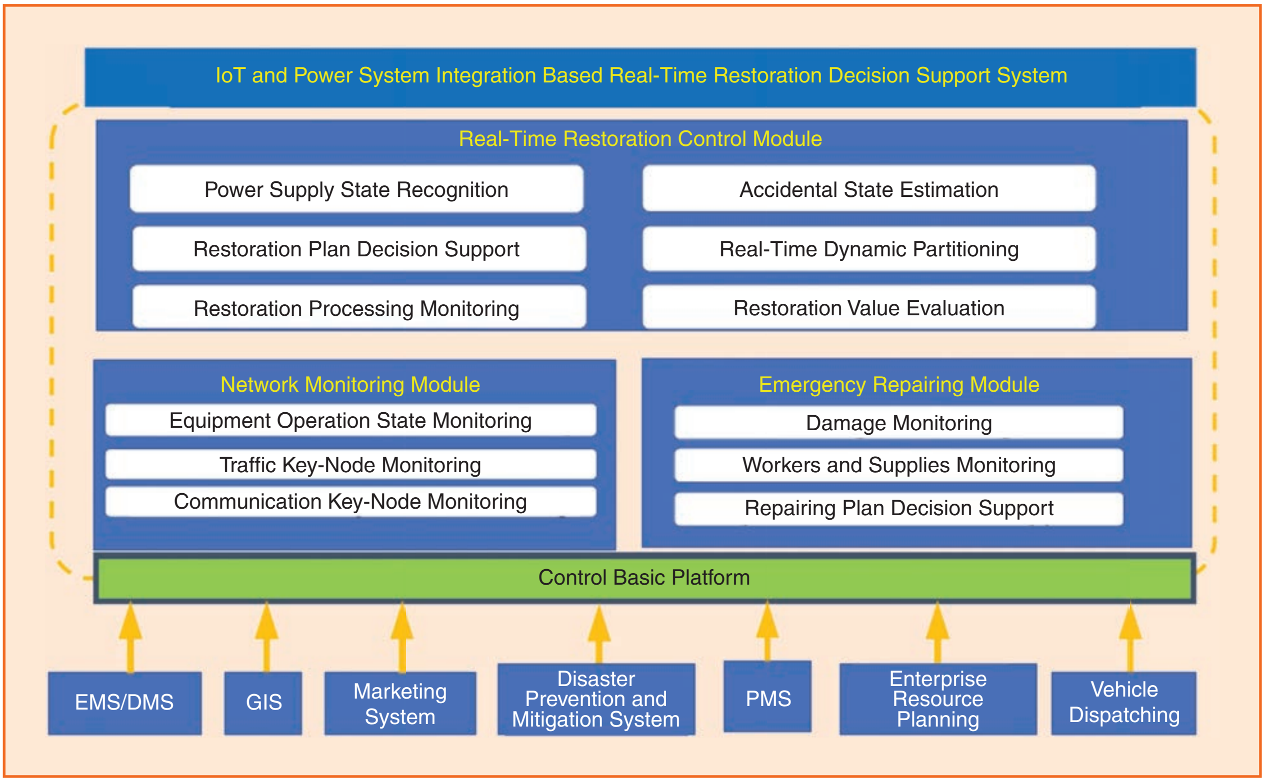

figure 7. The decision support system.

> With a typhoon, disaster damage could include broken poles, tilted poles, broken lines, flooded station rooms, and flooded ring network cabinets.

Emergency Personnel and Materials Monitoring

According to the material ledger, the types of statistics are made to distinguish wire, distribution transformer (e.g., table transformer, box transformer, special transformer, oil-immersed type, or dry type), tower (linear rod, tension-proof rod, and so on), and insulator string (tension-proof rod, overhang, and so on). Statistics are then made according to the following matching method:

1) *preliminary judgment*: DMS and SCADA systems provide disaster loss information and fault type. Unmanned aerial vehicles are responsible for onsite mapping. They use video identification to determine faulty poles and tower lines and determine the type of materials needed.
2) *on-site judgment*: Upon arrival, the emergency repair team confirms and supplements the damage information. The team further matches the type and quantity of materials according to the type of failure.

Emergency Repair Plan Optimal Decision Making

The cooperative optimal decision-making strategy of the distribution network emergency repair scheme can comprehensively consider network remodeling with changes in topology and fault emergency repair scheduling. Fault emergency repair scheduling includes construction personnel and emergency materials. The cooperative optimization model for distribution network recovery is established and divided into two layers: network remodeling and fault repair scheduling.

An artificial intelligence approach is used to develop the emergency repair plan. A genetic algorithm, based on evolution processes in biology, determines the connection state of the line in the network frame reconstruction. A simulated annealing algorithm is used to determine the fault repair plan. Based on the preliminary damage information, the dispatch plan is derived for the emergency repair team and materials.

Real-Time Restoration Control Module

As also shown in Figure 7, the real-time restoration control module consists of the following functions.

Power Supply State Recognition

The state before the fault occurrence of the distribution network, unrecoverable area, and power supply state of the plants can be identified according to the physical damage of the power supply equipment. From the power flow information of the main network, the bus with power demand is used to search for the available power combination of the distribution network and multiple feasible microgrid statuses reported from the interface bus. All power-on systems originating from the distribution network, except the distribution power reported to the main network, are reported to the main network as residual loads.

State Estimation for Power Outage Accidents

The power outage load was determined, and the power outage accidental level was evaluated. Power deficiency information is submitted from the city power network to the provincial power network according to the load recovery demand information and available power supply information.

Real-Time Dynamic Partitioning

There are many available power supplies, such as

1) the power supply from the provincial power network
2) the power supply from the adjacent network
3) the power network black-start power source at the corresponding level
4) corresponding network islanding
5) electric vehicles
6) the city power network.

The online system divides each power supply recovery partition according to the aforementioned power supply characteristics, power equipment recoverability information, and power distribution in the region.

In the case of a major power failure (e.g., a power failure of the provincial power network), the power failure area can be divided into several small areas by making full use of the DG and recoverable nodes in the distribution network. The recovery process considers the network topology and the distribution of important loads in the failure area through a series of switch operations. The main goal is to restore the load in the power outage area as much as possible through network division by considering electrical conditions and operational constraints to minimize the impact.

The basic principles of the recovery process are as follows:

- ✔ The zone shall contain at least one power supply for the starting distribution network (the recoverable node at the main distribution interface shall be considered as a power supply in nonisolated island areas).
- ✔ An intrazonal power balance shall be maintained.
- ✔ The power supply within the zone should be safe and reliable.

> After the distribution network receives the recoverable capacity from the main network, it optimizes the partition and the recovery scheme within the partition.

- ✔ It should be easy to switch from island mode to network-connected mode.

Dynamic partitioning means each node must be repartitioned after recovery. In this way, the system can respond to distribution network changes in the recovery process more quickly and make the recovery process more efficient.

If the power supply node in the zone is a DG that can support a black start in the distribution network, the island mode can be formed during the recovery process. The island operation must meet the following conditions:

- ✔ *Self-starting ability*: According to the operation regulations, all the DGs in the distribution network must be out of operation for a short time after the failure, so the DG participating in the island division should have a self-starting ability.
- ✔ *Ability of voltage and frequency regulation*: The starting power supply of the distribution network has voltage/frequency, or droop control, and reserves about 15% to maintain the safe and stable operation of the island.
- ✔ *Sufficient generation capacity*: The operation must withstand the short-time power impact from other non-black-start power supplies and ensure distribution transformer excitation loss and ac bus no-load loss remaining at a low level.
- ✔ *Stable output power*: Combined generator sets, passive inverters (and other excited generator sets), wind power generation, and solar power generation with energy storage devices can contribute to stable output power.
- ✔ *Communication and control capability with the distribution network dispatching center*: The division and operation of isolated islands rely on a unified management system, which should be equipped with remote communication and centralized control functions to facilitate remote measurement and control.

Restoration Value Evaluation of Power Station

The possibility and value of power station recovery were evaluated online, and the key stations and lines that affected the process of power grid recovery were determined. The effects of the shutdown station's recovery demand, surrounding plants' recovery demand, potential power supply, and potential transmission path are considered.

The recovery value of the target substation includes three aspects: benefit assessment, cost assessment, and risk assessment. The benefit assessment is divided into two parts, such as the recovery benefit of the load inside the substation and the potential recovery benefit of the surrounding power plants. The recovery benefit of the power plants considers five factors, including the unit value of each load, recovery capacity of each load, assessment time, electrical distance between the substation and the power plants, and system adequacy. The cost assessment includes voltage control cost (reactive power compensation) and switching operation cost. The risk assessment refers to the operational risk in the recovery process.

Recovery Scheme Decision Optimization

Recovery scheme decision optimization identifies partitions based on the recovery capacity of the power supply, dynamically updates partitions with the recovery process, and coordinates the power dispatch in different regions. To take load demand into account at all voltage levels of the substations, the recovery benefits of substations were calculated, feasible paths were searched to calculate the recovery costs and risks, and the importance of substation recovery was evaluated.

The importance of the substations in the zone is evaluated and arranged in descending order. The perturbation capacity is allocated to the most important one, and the load recovery benefit is calculated. The existing substations were incorporated into the active system, and their importance in the zone was reviewed. The perturbation capacity was allocated to the substations with the largest importance. Each allocation is partitioned, and the importance of the subsystem is determined until the recoverable capacity is allocated. Each partition is restored in parallel, and the power distribution recovery scheme within the partition is optimized.

In the next step, the revenue information in each zone is sent to the main network. After the distribution network receives the recoverable capacity from the main network, it optimizes the partition and the recovery scheme within the partition. Finally, the recovery plan is implemented based on the optimal solution.

During the plan execution, the power transmission path is first searched in each zone, and the grid security, like equipment overload, generator self-excitation, air-filled transformer, and line safety, is checked to improve the operation's success rate. By considering the recovery capacity of the power grid and the recovery demand of power stations, the candidate recovery scheme is formulated in each zone. This includes the power transmission scheme of power plants and the transfer scheme for important load substations. The recovery benefits, transmission risks, and costs of the plant are calculated.

> By considering the recovery capacity of the power grid and the recovery demand of power stations, the candidate recovery scheme is formulated in each zone.

Restore Process Monitoring Evaluation

With the restore process monitoring evaluation module, the recovery plan is stored and managed. The recovery progress is evaluated based on the actual implementation of the recovery plan. The monitoring and management of the recovery process include:

1) tracking and monitoring the execution process of the current recovery task of the power grid
2) updating the status information of the power transmission or emergency repair equipment in real time
3) monitoring and managing the relevant information of the emergency repair team and spare materials for the power grid
4) monitoring the latest load recovery requirements for both the current grid level and the subgrid.

The demonstration project "Online Power Supply Restoration Control Decision Support System" was commissioned in June 2020. The system consists of IoT connectivity of smart devices and a power system integrated network. The system

1) realized the minute-level grid online restore control decision support
2) evolved from offline recovery plans to online resume decision scheme
3) improved the capability of the regional power grid power supply recovery and power supply service level
4) guaranteed the power supply security and reliability of the important regional load.

The overall disposal time of power failure accidents is reduced by at least 30%, and the loss of power failure of the regional power grid under extreme disaster weather is greatly reduced. The online prediction, warning and risk prevention, and control of the power grid to natural disasters are realized. The alarm rate of power grid operation risks caused by external disasters is guaranteed to be less than 20%.

Under the early-warning mode, the decision making of power grid potential risk prevention and control can be achieved in less than 10 min. The passive postdisaster repair is replaced by an active predisaster warning to improve the disaster prevention capability of the regional power grid.

Final Note

This article shares a review of experiences from three Chinese projects. It explores resulting guidelines and recommendations to help promote the deployment of smart energy systems that maximize decarbonization and smart city development. Challenges arising from the projects are as follows:

- ✔ The existing auxiliary decision-making means are insufficient.
- ✔ There is a lack of efficient collaborative decision making between different dispatch levels.
- ✔ There is an inability to timely obtain and integrate data of all scheduling levels and the relevant departments.
- ✔ There is a lack of online assessment tools for emergency needs.

To address these challenges, a better coordination and management system is needed. Future work along these lines is under development.

For Further Reading

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