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Perspective of active distribution network for industrial application

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Abstract

This paper proposed the concept of Industry Active Distribution Network (IADN), analyzed technical issues and illustrated the realization of IADN according to industrial customer requirement. IADN would bring a great technology revolution to present Industry Distribution Network (IDN). The innovation by IADN was elaborated from three aspects: system architecture upgrade, system utilization enhancement and system reliability improvement. Particularly, architecture planning methodology, energy harvesting technique, and real-time communication technology in IADN were emphasized. The related implementations were discussed in this paper based on the IADN laboratory development.

Keywords: Industry distribution network; active distribution network

1. Introduction

Low carbon economic development concept has gained widespread attention and recognition in 2003. At present, the whole society realizes the importance of constructing low carbon economy mode in order to achieve win-win situation between social economic development and ecological environmental protection. The power industry has been the main energy foundation of Chinese national economy. Production of traditional energy from fossil fuels releases CO_2, which is 0.385 billion tons and is 50% of national total carbon emission in 2012 with rapid growth [1]. Utilization of Renewable Resource Generation (RRG) is a key method to promote low-carbon electricity production. But RRG high penetration also brings several potential problems, such as stable operation and power quality issue. Active Distribution Network (ADN) was proposed to solve these problems. Research project of ADN, such as High Tech Research and Development Programs (863 program) in China, demonstrates its feasibility and significant improvement of low-carbon economic development [2].

Currently ADN researches mainly focus on residential power grid whereas IDN, consuming over 70% power of China, is still relatively under development. In this paper, IADN is proposed by advancing ADN technology into industrial power system based on the equipment nature and system requirement of large industrial user.

Chapter one analyzed IDN characteristic, introduced ADN technology, and proposed IADN concept. Chapter two expressed the improvement of IDN architecture, advancement of IDN utility and enhancement of IDN reliability through adopting ADN technology. Chapter three mainly focused on problem and solutions about architecture planning, industry load energy harvesting and communication technology in IADN. Chapter four introduced IADN laboratory development. Chapter five summarized the paper with conclusions.

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2. Proposed IADN

2.1. Characteristic and requirement of IDN

In China, industrial electricity consumption was the main part of total electricity consumption. According to statistical data in 2015, domestic electricity consumption was 5.52 trillion kilowatts. Heavy industrial electricity consumption was 4.07 trillion kilowatts and it took 73.6% of total electricity consumption, where 58% is from heavy industries.

Due to unique characteristic and requirement of heavy industry consumer, IDN is different from Traditional Distribution Network (TDN) [3] in Table 1.

Upgrading IDN to a smart level can greatly reduce China's energy intensity and solve issues mentioned above. Due to the urgent need for economy development, IDN upgrading could one of the key factors for a sustainable growth in China.

2.2. Introduction of active distribution network

ADN manage power flows through active control of local Distributed Energy Generation (DER), Distributed Electrical Energy Storage (DEES) and Controllable Load (CL) [4].

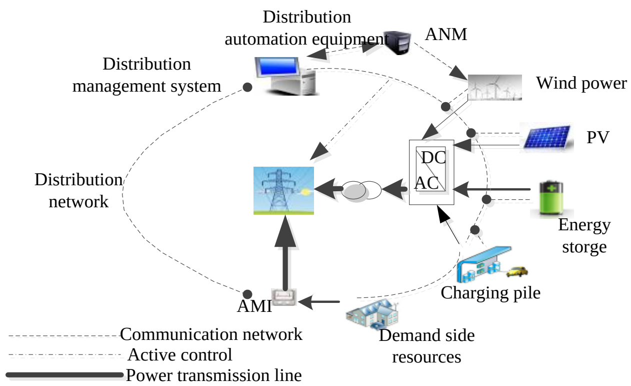

Fig. 1. Typical elements in active distribution network.

Table 1. The difference between TDN and IDN

Category	**Characteristic of IDN**	**Characteristic of TDN**	**Comparison and analyze**
Capacity	Industrial energy consumption is 70% of total energy consumption in China	Other energy consumption is about 30% of total energy consumption	The impact of large industrial consumer is more significant
Characteristic of distribution network	IDN contain internal power supply, such as self-generation which capacity is less than 100MW.	TDN doesn't contain internal power supply.	IDN control strategy is more complex due to internal power scheduling.
	Most IDN network structure is looped network. Critical load require double power supply.	Most TDN network is looped network or radial network.	The cost of looped network is higher and utilization rate is lower in IDN.
Requirement of power supply	The reliability of IDN has an important influence on industrial safety of energy supply	Reliability of TDN is less important influence on civil consumer.	IDN reliability requirements are higher.
	Power quality requirement is higher in IDN because of industrial equipment sensibility.	Power quality is less important and follows standard in TDN.	Requirement of power quality in IDN is higher than it in TDN.
	Reactive power compensation is more important, especially medium and low voltage network	Reactive power compensation is less important	The reactive power demand of IDN is more important than that of TDN.
Effect of load characteristics	The single load of IDN is large, which has strong impact on the power grid and	The single load of TDN is small which has small	Impact of the single load is larger in IDN than it in TDN.

	has the characteristics of nonlinearity and intermittence.	impact on the power grid.	
	Peak capacity of IDN is higher because of numbers of motor sand transformers installed.	Peak capacity of TDN is lower.	Equipment Utilization of IDN is lower than it in IDN.
	IDN load is centralized and supplying distance of power source is close. Transient stability problem is not obvious.	TDN load is dispersive and supplying distance of source is far. Transient stability could be a problem.	
Loss	Chance of IDN loss is high (exp. The loss of distribution network is above 10% in steel industry[5])	Loss of TDN is not often	Chance of IDN Loss is high due to lower power factor.
Present situation	A few parts of operation and testing equipment is being upgraded to intelligent device in IDN	Operation and testing equipment has adopted DER and ADN technology	IDN upgrade and renovation opportunity is huge

As shown in Fig. 1, system component of ADN consist of various Distributed Generation (DG), Distribution Electrical Energy Storage (DEES) and Controllable Load (CL). As black line shown in Fig. 1, these devices connect to distribution network through power electronic components. ADN control system includes advanced metering devices, such as Advanced Metering Infrastructure (AMI), distribution network management system and distribution automation equipment. Through high-speed communication system in the distribution network, these devices form control network by Active Network Management (ANM) as the dotted line.

ADN was realized by system control which manages power flow and sets special operation goals, through active supply management and demand side response. ADN adoption also requires the participation of three parties: distribution network, energy consumer and renewable energy suppliers. The active control include six aspects shown in Table 2 [6]. All aspects work together to achieve system optimization goals ultimately.

2.3. The concept of IADN

According to comparison and analysis in Table 1, problems mainly found in IDN include system planning, capacity design optimization, power supply management and control, distribution network reliability, power quality improvement and characteristics improvement of demand side load. In Table 2, it is visible that all six categories have respective issues. Therefore, IADN concept is proposed so that ADN technology can be applied to solve industrial applications problems.

Renewable energy is good complementary of traditional energy sources in industrial application, such as photovoltaic power generation, small wind generator equipment and electric vehicles. Renewable energy and controllable loads has gradually formed system architecture to build active distribution network in IDN [7].

Smart meters and other sensing & communications equipment make IDN smarter, which becomes the foundation to form safe, reliable and efficient energy system and optimize industrial energy architecture. Intelligent measurement device and communication equipment can collect energy consumption data of different production steps in different industrial types. These data are the core information for the transformation from traditional production to smart production.

The direction of IDN development is integrating distributed power architecture with legacy system for a smart energy and production based industrial environment by ADN technology.

3. Improvement of IDN by IADN

3.1. Upgrade of IDN architecture by IADN

The IDN structure is the radial network. In order to improve the reliability of power supply, the design regulation requires double independent power supply for critical load. As black line part shown in Fig. 2, it is a typical electrical schematic of coal mine power distribution system, including two independent power supply line L1 and L2.

Design capacity of L1 and L2 is selected to be the peak capacity of system load. One line is always in hot standby mode whose capacity is fully redundant most of the time. Because IDN was set at the edge of power grid and constructed at earlier stage of the coal mine, it was not considered for later system expansion which makes it difficult for network architecture upgrading. DER and DEES had the advantages for the flexible distribution architecture, short construction period and low investment cost that can compensate these defects as red line part in Fig. 2.

Table 2. Six aspects of active control in ADN

Dominant object	Active content	Function implementation
Distribution network	Active planning	Planning, construction and operation are coordinated. Power system, monitor system and intelligent control system should be integrated during planning stage for overall optimization.
		Active planning of power supply and load is adopted. The design and requirement is proposed according to distribution energy capacity and distributed generation resources in this region.
	Active control	Active control ensures the safety, stability and efficiency by collecting real-time system information and judging abnormal operation.
	Active management	Active and reactive power management is adopted.
	Active service	Requirement of electricity and power quality should be met.
		Power and backup is provided for superior power grid through demand side response.
Load consumer	Active response	Improvement of load characteristics and the grid resources utilization can be realized by demand side response.
Renewable energy suppliers	Active participation	It increases the power grid capacity through the optimization of the output performance for distribution power supply.
		Distributed energy interacted with power grid friendly through power quality management function.

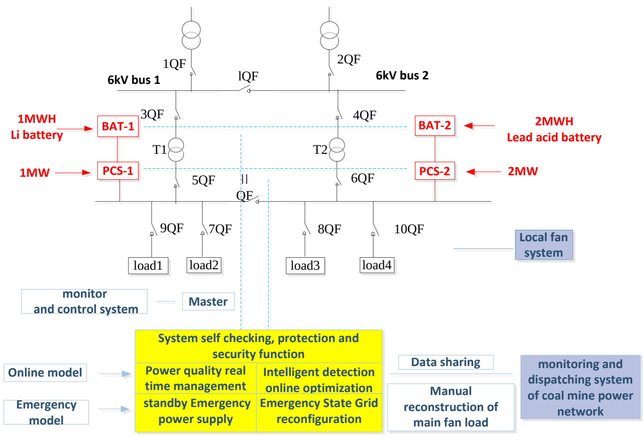

Fig. 2. Schematic diagram of an industrial distribution network.

3.2. Improvement of utilization of IDN by IADN

As mentioned above, extra hot standby line designed for system safety was not fully utilized. DER and DEES installed in IADN can operate as extra standby power supply to guarantee the system safety. This upgrade can save standby capacity cost before system is being designed, or utilize standby capacity after system is being built. Because DER and DEES were widely used in IDN, system must provide extra energy margin based on probability of load consumption pattern. This energy margin can operate as emergency power supply to replace special-designed emergency equipment.

According to IDN load characteristics in Table I, power inrush demand will increase design margin and lead to capacity waste. DEES can balance intermittent uncertainty of generation feature and load nature. Random fluctuations of DER and load can match each other through active regulation. Both of them can provide capacity margin to meet the needs of short-term peak power.

3.3. Improvement of reliability of IDN by IADN

According to the analysis in Section B, distributed standby can be applied in IDN as standby line or emergency power supply. The feasibility of this scheme can be preliminarily proved by calculation of failure rate.

As shown in Fig. 3, primary supply link is P_{SL} , and reliability is r_{SL} , and annual working time is Y. Reliability of primary & second supply link is $r_{SL}{}^2$. If power supply link is single link, the standby capacity of emergency power supply C is calculated as shown in equation.

$$C = P_{SL} \cdot Y(1-r_{SL}) - P_{SL} \cdot Y(1-r_{SL})^2 = P_{SL} \cdot Y \cdot r_{SL} \cdot (1-r_{SL})$$

System emergency capacity is C and reliability goal is $r_{SL}{}^2$. When $r_{SL}{}^2 = 80\%$, if number of DER and DEES is n, and their capacity is C. Reliability of each DRE or DEES is r. so the reliability of system is: $\left(1-(1-r)^n\right) = 80\%$ ·

Requirement of reliability of each DER or DEES is in Table 3, according to the difference of n number.

Table 3. Reliability requirements of a single node in the system according the number of nodes

n	r
2	55.28%
3	41.52%
4	33.13%
5	27.52%

Assuming the number of available DER or DEES is n, and capacity of it is C/m in system. The reliability of it is R. The system reliability is: $C_n^m r^m = 0.8$, then reliability requirements of each node is shown in Table 4(n>m>1).

As shown in Table 4, when n is 20, 40, 100 and m is 10, 20,50, the corresponding requirements for single node reliability is respectively 29.08%, 27.43%, 26.18%. According to relationship between the capacity of the whole system, single node capacity and single node reliability Table 4, Fig. 3 depicts the relationship diagram of them.

Table 4. The reliability of the single node according total number of energy nodes and capacity of single node

n	m	r
20	10	29.08%
40	10	12.52%
40	20	27.43%
100	50	26.18%
150	50	15.56%

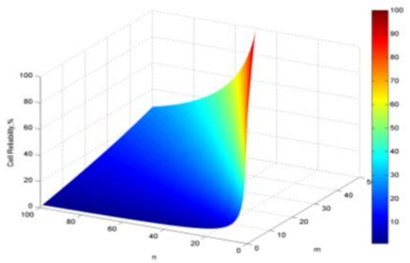

Fig. 3. The relationship between capacity of a single node, reliability of a single node and total number of energy nodes in the system.

The calculation evidenced that, in system with same total capacity, the single node capacity is smaller, the requirement of single point reliability is lower and the system is more reliable. The system reliability continues to improve with more DEES in the distribution network, which can satisfy the original requirements for reliability design of IDN.

4. New Problems and Solution in IADN

ADN is the advanced technical direction of IDN, which includes different part, such as: distributed energy planning forecast, power load prediction technology, demand side management technology, distribution network system planning, optimization of system planning, management and operation of distribution network, interactive of source-grid-load, different demand of economic from different participator, distribution network communication system, control architecture and so on problem [2, 8]. These problems also need be solved in IADN.

This chapter focused on three problems: IADN architecture planning, energy harvesting technique and communication technology applied in IADN.

4.1. Planning of distributed architecture in IADN

In ADN, the purpose of distributed energy planning is cost-saving. This optimization planning designs installation location and capacity of DER and DEES in TDN. The purpose is the maximization in power output of RRG [9].

According to the description in Section III.B and III.C, in IDN, planning goal is system safety & reliability. The solution is designing distribution energy configuration to meet safe supply demand of system energy. So calculation input is energy margin, and its result is parameters of distributed energy type, number, individual capacity, power and the installation location.

IADN architecture planning is a reverse thinking process of ADN planning. This method is more used in load demand confirmation case as shown in TDN design.

4.2. D2G based energy harvesting concept in IADN

Electric Vehicle (EV) has been accepted to replace raditional automobile with extra features. When EV is not used, aggregated battery could be dispatched for power grid ancillary service such as peak-shaving, freq. regulation, renewable energy smoothing etc. [10]. So vehicle to grid (V2G) concept has obtained the wide-spread attention.

In the industrial park, commuter vehicles and freight vehicles have been replaced by electric vehicle gradually. Industrial vehicles operation is more periodic and more controllable than passenger vehicles. In IDN, DER could also include more features by adopting V2G technology.

In the IDN, motor load accounted for 75% of total industry electricity consumption. Motor released energy during regeneration process. But so far, energy harvesting of regulating and braking motor has not been fully paid enough attention, for example oil drilling rig [11].

Based on V2G, this paper propose a concept of drive to grid (D2G) technology, that could harvest motor regeneration energy as new kind of distributed energy source by using DEES device in distribution network. The system can greatly improve the energy utilization of overall system.

Based on D2G concept, motor load in industrial application could take advantages of adding storage component inside variable speed drive for D2G application in IADN system. This could harvest 10-15% overall energy consumption in overall industry application.

4.3. Big data real time communication in IADN

1) Communication architecture and technology in TDN

Communication network in distribution network is an important information channel to ensure normal operation, fast fault response, resources utilization, and real-time response service. As solid block shown in Fig. 4[12], communication system is independent according to different business operation unit in

TDN, which is not compatible and efficient . Intelligent communication network re-integrate business unit into five units in order to improve effectiveness and compatibility, as dashed box shown in Fig. 4.

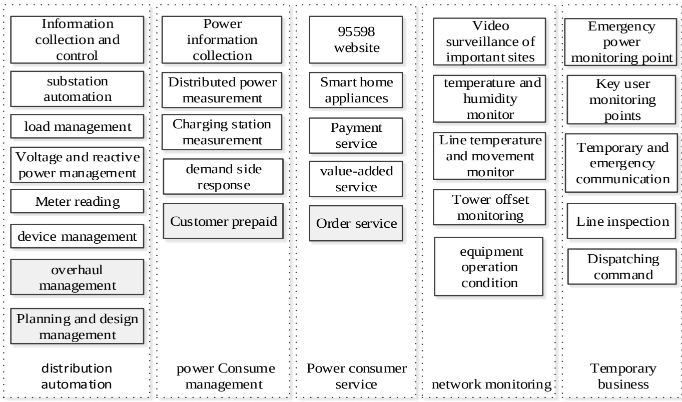

Fig. 4. Business divisions in distribution communication network.

At present, wide area measurement system (WAMS) technology and AMI technology are widely used. Data communication adopts centralized processing mode, the dispatch center collect operation data and real-time data of generation unit and electricity load [13]. In TDN, the data standard and standardized protocol are object centered system, which relies on server capacity and communication bandwidth, and communication node architecture. The reliability and expansibility of it are also relatively low and communication architecture is not suitable in ADN system.

2) Data distribution service (DDS) application in ADN

Differences of communication structure from equipment suppliers with different function purpose have made complex industrial communication architecture and mode. The communication system have undergone profound changes, as lists shown in Table 5 [14].

Centralized network structure, centralized data acquisition and processing methods cannot meet the demand of IADN. Researches have been focused on new communication technology which is suitable for requirement of peer to peer communication, low latency, two-way flow of data, network openness, and high real-time communication, such as DDS and so on [15], [16].

Table 5. The communication system difference between the current network and IADN

Characteristic of IDN	**Characteristic of IADN**
Centralized	Distributed & centralized
One-way flow of information	Two-way flow of information
Fixed load	Random load
Analog signal	Digital signal
Single target	Multi-function
Exclusive standard	Open standard
Mainly isolate operation	Mainly based on cooperation
Non real time data	Real time data
Not connect to OT/IT	Connect to OT/IT
Restrict consumers to interact	With virtual shaking hands, open consumer interaction
Maintain data center security	Maintain information security in enterprise wide
Easy crash network	Recovery network

DDS is real-time data distributed service based system data dissemination protocol issued by Object Management Group (OMG). At present, successful application cases are in the military, marine and aerospace fields[15] .

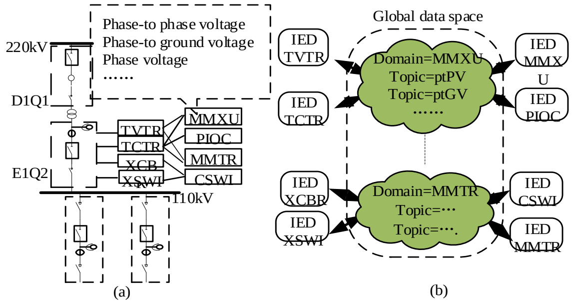

Fig. 5. Data model of IEC61850.

The DDS protocol uses the data centric publish/subscribe (publish/subscribe) model. Each node can publish or subscribe to data. Fig. 5(a) shows the object centered communication mode. Fig. 5(b) showed DDS communication mode. Compared to two modes, the nodes in DDS protocol can be directly involved in the data exchange, not through the server adapter. The devices coupling effectively reduced by distinguishing data information by definition of domain name.

In communication test, each data packet is 164bit. When the data transmission rate is higher than 2600 packets / s, communication systems appear packet loss phenomenon; when the data transmission rate is up to 10000 package / s, stability and reliability in the 74.7%[15]. So DDS technology an meet efficient and reliable requirements in IADN.

5. Introduction of Experimental Platform

This chapter introduces control system architecture, distributed energy management systems (energy operating system, EOS), laboratory platform and application case.

5.1. Control system architecture in IADN

Considering nodes number, characteristic of centralized architecture and distributed architecture, hybrid hierarchical structure can ensure real-time and reliability requirement of control system, which contain device layer, mist layer, fog layer and cloud layer. Device layer control equipment, whose interface is voltage/current reference. Mist layer balance energy, which provide control reference to device layer by calculating. Fog layer control power flow in distribution network composed by multi mist layer. Cloud layer collect the network data and analysis it.

5.2. Distributed energy management system (EOS)

In control system architecture, communication system can effectively exchange data between four layer based on DDS technology. EOS can accurately judge the running state, and exchange information securely. Real-time control of the system can realize online/offline simulation, which improve the stability and economy of system operation. And EOS is hierarchical and modular architecture which solve problem of large span area, wide time span, and different equipment. This control and monitor of distributed energy system can be realized in different time scale.

In mist layer, EOS collected device information, judged the operation status, provides control commands, realize the information interaction, and decide energy transmission direction. In the fog layer, EOS collected mist node information, calculate power trend, interact information. in fog layer, EOS construct the operating condition and determine the stability. In the cloud layer, EOS collects all data and analysis it.

EOS hardware is shown in Fig. 6. Communication network is composed of DDS PC, cRIO and host PC based on DDS protocol. The DDS PC is data acquisition device. cRIO is data processing device in fog and mist layer based on NI platform. The host PC is data storage, analysis display platform in cloud layer.

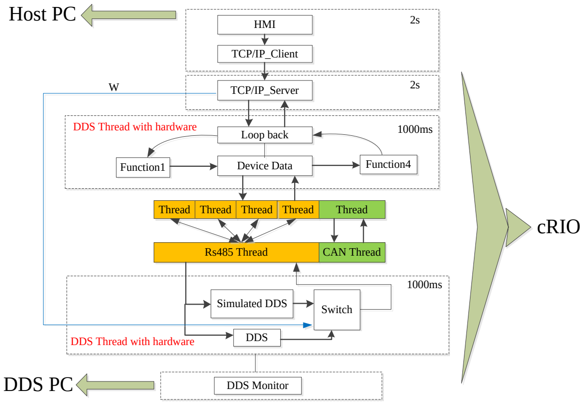

Fig. 6. EOS hardware system platform.

5.3. IADN power laboratory platform

Circuit topology of platform is shown in Fig. 7. The system contains AC bus and the DC bus, which can segmental running through the switch KB35, KB36. Power system include following devices: a variety of energy input, DEES, load and motor. Motor M1, M2 and M3 can control the energy flow between the buses. Platform connected large grid. These facilities are hardware foundation of interactive control between source-network-load in IADN.

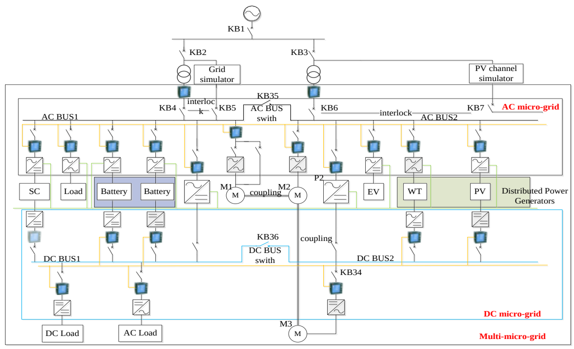

Fig. 7. Schematic diagram of the experimental platform.

5.4. The application of EOS frame-work in IADN

EOS frame-work was used in the upgrade and reconstruction of Shenhua coal mine which was shown as black line part in Fig. 2. Distribution network of Shenhua coal mine installed MW storage system during reconstruction process. EOS was used to realize data acquisition and monitoring. And cRIO control logic and manage device according to mine coal operation demand. Fig. 2 is distribution system diagram of Shenhua coal mine after reconstruction. Storage device was red line part in Fig. 2 and control system is blue line part.

5.5. The future work of laboratory platform

Laboratory platform is used to develop IADN technology and solve common problem in IDN which is found in real application. Firstly, common communication standard is being studied and DDS based middleware is being investigated to provide real peer to peer data-exchange mechanism for distributed energy control. Secondly, based on a MIST-FOG-CLOUD architecture, an EOS frame work is being developed for next generation distributed grid control in multiple distributed bus configuration. In the end, a feasible field solution and design could be certified for IADN application through real time simulation and hardware-in-loop methodology.

6. Conclusions

This paper proposed IADN concept which takes advantages of ADN technology in IDN. The innovation of IADN brought advancements in three main aspects: architecture upgrade, utilization enhancement and reliability improvement. Major problems and possible solutions were discussed in the paper. Related implementations were verified in laboratory platform.

In the future, IADN technology could be adopted to optimize the balance of the demand and supply in industrial energy system. Distributed storage will be the key smart asset to minimize the redundant energy capacity to meet system safety requirement. Effective distributed control will realize the dynamic balance of power flow between source, storage and load. The final goal is to reach global economic optimization for consumer, generation unit and power distribution network.

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