Study and Application of the Integrated Energy Management and Service System

Zheng Tao, Dai Zemei, Cao Jing, Chi Yawei and Xu Wei

Abstract The expansion of business management and outward service of new market participants, for example integrated energy service corporations, results in the increasing demand for developing the integrated energy management and service system. By analyzing the business feature of integrated energy, a comprehensive system architecture, which features distributed self-control, centralized coordination, hierarchical operation and bidirectional interaction, is proposed to match the characteristics of multi-type, multi-operator, multi-customer and multi-service requirement of IES. Core techniques including comprehensive steady energy-flow model, IES comprehensive decision-making based on hierarchical analysis were studied. The effectiveness, applicability and functional completeness of the proposed system architecture are demonstrated by its successful application in practical projects such as Tongli Project.

Keywords Integrated energy system (IES) · Smart grid · Energy internet · System architecture · NIES5000 platform

1 Introduction

Energy is an important and decisive factor in economic and social development. There exists various types of energy systems in industry production and human life, such as electricity, natural gas, heat and cold. Different kinds of energy have their own advantages, meanwhile they can be replaced by or transformed into each other.

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Therefore, people have recently proposed the Energy Internet (EI) [1–6] based on the smart grid. To catch up with the rapid advancement of China's power system reform, traditional energy companies, such as State Grid, China Southern Power Grid, and ENN Group, have expanded their business scope from single energy supply to integrated energy service. The appearance of new market entities such as electricity suppliers for incremental distribution network, and integrated energy service providers, brings changes to the energy supply methods and consumption patterns. New forms of integrated energy services are created to meet the increasing demand for energy management, optimal control and value-added services for integrated energy, which plays an important role in improving energy utilization efficiency, optimizing energy structure, and promoting the competition and cooperation. The power grid is the core to integrated energy system (IES), because electricity is much easier to be transported, converted and used, compared to other forms of energy. Before the establishment of the IES, the smart grid has been fully developed, which can provide a great demonstration and reference for the development of IESs.

The IES has received worldwide attention [7], with lots of studies carried out focusing on its overall structure. The American National Renewable Energy Laboratory (NERL) proposes the Electricity Distribution Bus (REDB) approach to connect the energy layer, device layer, simulating test layer, monitoring and data acquisition layers [8, 9]. Professor Pasquale Andriani et al. proposed a basic architecture for the Future Smart Energy Internet Project (FINSENY) consisting of the smart energy application layer, intelligent energy information communication technology (ICT) layer and user layer [10, 11]. Professor Hongbin Sun's group from Tsinghua University draws on the concept of smart grid EMS family [12], pointing out that the basic structure of energy Internet consists of two layers: "Internet-like energy system" and "Internet plus". To adapt to the requirements of multi-agent management, they proposed the multi-energy EMS family concept and distributed architecture. Energy management can be achieved through self-discipline and synergy among the family members [13]. Professor Tao Zhang of National University of Defense Technology proposed a hierarchical controlling architecture, which is suitable for the energy management systems (EMS) of energy Internet [14]. Based on the construction of Beijing Yanqing Smart Grid Innovation Demonstration, Renle Huang, from Beijing Electric Power Company, designed a fundamental structure for energy Internet, containing energy production and consumption layer, energy transmission layer, big data platform layer for integrated energy management, and application layer [15].

The architecture researches on integrated energy management systems mentioned above are mainly focused on the management and controlling optimization for integrated energy, with low correlation to smart grid and weak support for the development and interactivity for integrated energy services. Some investigations only proposed the ideas or concepts on architectural level, lacking of various projects verification for the practicality of the architectures.

In the present work, an overall architecture system, with smart grid as the core, is proposed for integrated energy management and service system (IEMSS), based on the analysis of the characteristics of IES. We analyzes the key technologies of integrated modeling for steady energy-flow, joint dispatch and comprehensive decision making. Furthermore, the integrated energy management and service system NIES5000 was developed based on the proposed system and key technologies. Its feasibility, flexibility and integrity has been validated by the successful application practice in several domestic projects.

2 The Overall Architecture of IEMSS

The conventional micro-grid EMSs often employ the centralized structure of "information and decision-making concentration" [16], which is mature enough to meet the requirements of safe and economic operation. However, with the appearance of IESs, the conventional micro-grid EMSs can no longer meet the requirements of monitoring, coordinated optimization and scheduling of multiple energy sources. Therefore, based on the "architectural characteristics of hierarchy" [17], a new architecture of EMS is proposed in present work, considering the business characteristics of the IES. Characterized as "distribution self-discipline, centralized coordination, hierarchical partitioning, two-way interaction", this architectural is divided into five layers from bottom to top, as shown in Fig. 1, including distributed self-discipline user layer, energy internet layer, partition management area layer, collaborative management center layer, and supply and demand interactive service layer.

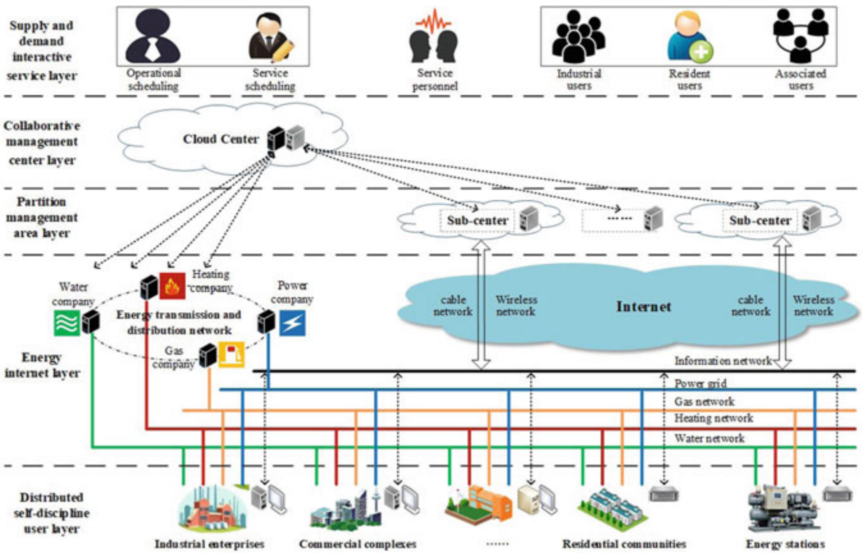

Fig. 1 The overall architecture of integrated energy management and service system

(1) **Distributed self-discipline user layer**. Industrial enterprises, commercial complexes, residential communities and other users as well as regional energy stations are usually energy sub-grids which contains heterogeneous energy sources such as electricity, water, gas, heat and cold. In order to achieve higher economic or environmental benefits, the subnet can be connected to the superior IEMSS of the upper level as an energy node, which is helpful to give full play to the adjusting ability of the controllable resources in the subnet.
(2) **Energy internet layer**. This layer consists of energy transmission and distribution network, information Internet, and externally accessible energy management system for electricity, water, gas, heat, etc. By means of the information Internet, the energy subnets physically distributed in each user station form a logical centralized energy information network, where each insider user can share the adjustable resources and exchange energy information. The energy transmission and distribution network is the carrier of energy flow. Therefore, the access of various energy management systems, which is the foundation of multi-user energy optimization, can realize the interaction and integration of various energy operation and measurement data.
(3) **Partition management area layer**. As a resource allocation center for rapid response to energy services in IEMSS, this layer usually has one or more sub-centers, depending on the requirements of fragment management for energy service. The regional sub-center can be merged with the cloud center if there is no requirement for fragmentation management.
(4) **Collaborative management center layer**. As a supervision and scheduling center for IEMSS, this layer exchanges data through standardized interfaces with third-party systems. It is in charge of the centralized control and service allocation for regional sub-centers or user stations.
(5) **Supply and demand interactive service layer**. As the supporting layer for the information release and service interaction of the IEMSS, this layer allows operators to dispatch regulatory services of the energy information network, such as monitoring, optimization, measurement, billing and transaction, to schedule service personnel as well as competitive service including analysis, evaluation and emergency maintenance. Industrial users, resident users, government and other associated users could enjoy online services through web pages and APPs.

Compared with the energy management system of conventional micro-grid, the IEMSS proposed in this paper has the following characteristics:

(1) **Integrated Platform**. The IEMSS provides an integrated support platform to achieve integrated modeling for multi-energy & multi-service, integrated acquisition and processing of multi-data, integrated management of multi-user, multi-service integration and integration display for multi-application.
(2) **Flexible deployment**. The IEMSS provides different choices from small scale to large scale, which can be deployed separately or in a cloud environment and adapt to different security level requirements. This IEMSS could satisfy the

increasing demand from the user group in different stages of the business development, and could also take into account the needs of all participants to build the system.

(3) **Interaction of supply and demand**. The IEMSS provides an interface for the interaction between service provider and demander. The two parties can share information, energy and value through the system, which improves user participation and system stickiness.

3 Functional Design of Energy Management System for Integrated Energy

The conventional micro-grid EMS system usually targets at the safe and economic operation of the grid. It only needs to optimize the electricity dispatching with simple target and few constraints. While the IEMSS needs to ensure the safety and stability of the multi-energy system, under the constraints of operation, node balance, coupling, etc. It also needs to consider the overall efficiency, the absorption rate of green energy, and the pollutant. Therefore, compared with conventional micro-grid EMS system, IEMSS needs to integrate more complex functions.

Similar to the typical cloud computing architecture, the IEMSS contains three layers: infrastructure services (IaaS), platform service (PaaS), and software service (SaaS), as shown in Fig. 2.

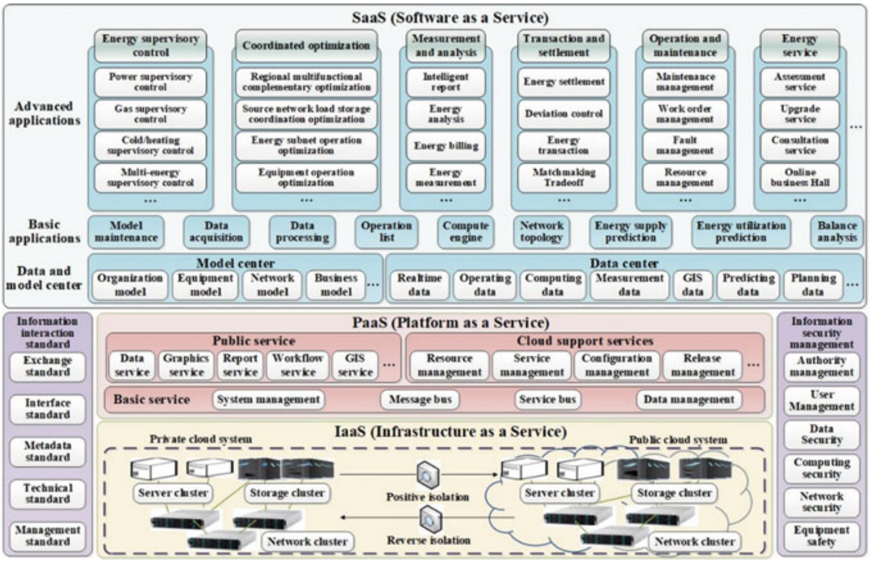

Fig. 2 Software architecture of IES

The IaaS layer provides virtualized computing, storage, and networking resources. The PaaS layer provides an online operating environment that supports the application's operation. The SaaS layer is the core of the IEMSS, providing users with a variety of application services, including the following categories:

(1) **Energy monitoring application**. The SaaS layer collects the information of various energy to maintain the balance between supply and the demand of integrated energy, guarantee the normal operation of pipe network and equipment, interact with other applications like maintenance and repairing.
(2) **Coordinated optimization application**. Various adjustable and controllable resources, such as the triple supply of cold, heat and electricity, distributed power, energy storage, charging piles, can be optimized and scheduled in three aspects: equipment operation, energy subnet operation, and complementation of regional multi-energy, resulting in scientific allocation and orderly use of energy, and improvement on energy efficiency.
(3) **Measurement analysis application**. Through the centralized collection and processing of measurements of integrated energy supply, the customer's overall and subordinate units are analyzed in terms of energy consumption, efficiency and cost, to provide data support for comparative analysis of optimization effects of energy optimized applications, statistical data release for energy service applications, analysis of energy saving potential, and consultation on energy conservation retrofits.
(4) **Transaction clearing application**. For the users trading outsourced energy or requiring self-management management, the SaaS layer allows them to purchase or sell energy in one-stop manner. It supports various energy trading modes such as protocol price and open bidding, guaranteeing a safe, open, fair, and efficient energy trading market.
(5) **Maintenance and repair application**. It provides GIS-based visual operation and APP-based mobile maintenance for cold heat and electricity systems. The whole process of various operation and maintenance services is managed in a standard and closed-loop way, ensuring the safe, reliable and efficient operation of the system. It also provides a fast, accurate and efficient cooperation mechanism for the user-side energy maintenance business.
(6) **Energy service application**. The industry and regional energy statistics are released through the online hall, which can provide users with comprehensive, one-stop, and diversified services, including consulting, query, withholding, payment, rapid repairing, maintenance, custody, energy-saving diagnosis, equipment transformation, and energy efficiency assessment.

4 Key Technology

4.1 *Steady-State Energy-Flow Modeling Technology for Integrated Energy*

In order to accurately describe the operation mechanism of IES for multi-energy type, a comprehensive energy integrative model is established in present work by combining different energy subsystem models and interface conversion equations, providing a base model for multi-energy complementary and schedule optimization.

(1) **Energy subsystem model**. The electricity, gas and heat subs-models of integrated energy characterize the distribution of steady energy-flow of different energy systems in the subsystem, including the electromagnetic model with the tide equation reflecting the voltage and power distribution in power system, as well as the thermodynamic and hydrodynamic models reflecting distributions of temperature, pressure, flow rate, and other physical quantity in the heat, gas, or other fluid systems. As shown in Fig. 3, the steady-state distribution of the subsystem in each group of models can be represented by algebraic equations. In Fig. 3, S_e, P_e, Q_e, U_e, I_e, Y represent separately the apparent power, active power, reactive power, voltage, current and admittance matrix in power system; P_h is thermal energy, C_p is heat coefficient, A_h is association matrix of heat network, v_{hm} is mass flow rate of heat network, T_{in}, T_{out} are the supply/return temperature of water or vapor in heat network, P_g is the gas horsepower, V_{gin} is inlet flow of power consumption equipment, α is the index for gas flow, η_g is energy conversion efficiency, P_{in}, P_{out} are inlet/outlet pressure of power consumption equipment, E_{in}, E_{out} are inlet/outlet energy of energy conversion equipment, H is conversion efficiency, $\circ$ represents Hadamard.

(2) **Conversion interface model**. The conversion interface model describes the conversion of steady energy flows between different energy systems,

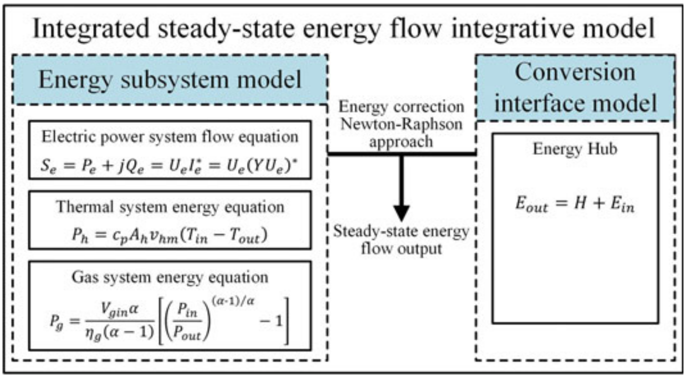

Fig. 3 Integrative model of steady-state energy flow in IES

correlating and coupling different energy systems. The conversion relationship between heterogeneous energy can be represented by an energy hub. In the energy hub model, a conversion efficiency matrix that characterizes the overall energy input to output relationship can be obtained by establishing the conversion coefficients between inputs and outputs for each energy.

(3) **Integrated model**. The integrated model can solve the steady energy flow of different energy subsystems under coupled conditions, providing the optimization base model for multi-energy joint scheduling. Firstly, the energy subsystem are integrated with the conversion interface model, and then the input and output energy at the interface are corrected by using conversion interface model and substituted into the corresponding energy subsystem. Finally, the steady-state energy-flow will be solved by using the nonlinear equation solving algorithm (such as the method of Newton-Raphson [18]. As shown in Fig. 3, the steady-state energy-flow integrative model for the integrated energy can exactly reflect the energy balance of the multiple energy-flow subsystem, and help to analyze the interaction between the steady-state energy-flows of the multi-energy system under equilibrium conditions.

4.2 *Comprehensive Decision Technology for Integrated Energy Based on Hierarchical Analysis*

In order to evaluate the service quality provided by IES to the multi-service objects and assess the overall operation quality of multi-service demand system, it is necessary to evaluate the effect of optimization scheduling on integrated energy through online evaluation and subsequent statistics. Therefore, this paper establishes the evaluation indicators that reflect different management and service performance, and then establishes the priority order of different evaluation indicators by using the method of Analytic Hierarchy Process (AHP). This set of indicators can provide comprehensive decision-making information for the dispatcher and other management personnel to determine the scheduling effect.

(1) **Evaluation indicators for integrated energy**. Based on previous research [19, 20], an evaluation index system for the IEMSS, as shown in Table 1, is established by referring to development experience of NIES5000 system. They are indispensable for the subsequent evaluation of the operational effects of the IES.
(2) **Comprehensive decision based on hierarchical analysis**. For the evaluation system including multiple indicators as shown in Table 1, it is necessary to establish the priority of different indicators in the decision-making process to facilitate the decision-making of dispatchers. Firstly, the decision weights of different second-class indicators are established by using the AHP method [32]. Then, after normalizing each index value and the corresponding decision

Table 1 Evaluation system of IES

First class	Safety	Economy	High quality	Environmentally friendliness
Second class	Load rate of pipeline/ network	Unit cost for energy supply	Qualified rate of energy supply	Amount of energy saving and emission reduction
	Failure rate of key equipment	Average cost for equipment maintenance	Energy complementarity	Substitution rate for electricity
	N−1 pass rate of equipment	Energy efficiency for integrated energy	Coefficient of valley to peak	Electrification rate of renewable energy
	Average time for incident recovery	Energy self-sufficiency	The complaint rate of users in recent 7 days	Local absorption rate of new energy

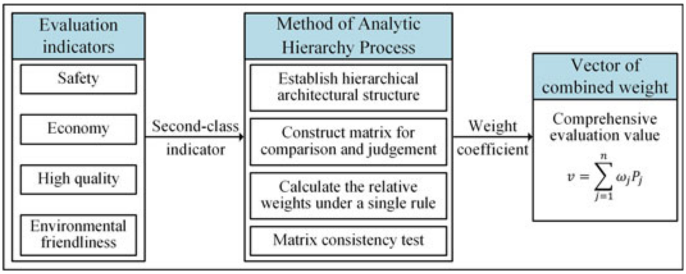

Fig. 4 Diagram of AHP-based comprehensive decision

weights, the weighted sum of the system comprehensive indicators is obtained to measure the overall optimization scheduling effect of the system. As shown in Fig. 4, ω_j and P_j represent the weight coefficient and the evaluation value of the jth index, v is the comprehensive evaluation value.

5 Applications

According to the architecture system and key technologies proposed in present work, the author's team developed NIES5000, the management and service system for integrated energy system, which has been initially applied in several projects such as Tongli project. Based on the application of these projects, the following conclusions can be drawn:

(1) For different types of projects (park users, integrated energy suppliers, incremental placement companies), the architecture proposed in present paper can satisfy the requirements.
(2) The architecture proposed here can provide flexible architecture for the different characteristics of various projects and specific individual demands. For example, small- and medium-sized projects at the industrial park can be deployed as first level. Large and medium-sized projects such as distribution power companies and integrated energy service providers can be deployed at multiple levels. Private deployment and Internet deployment can be flexibly selected based on service range and mode. Security zone and Internet zone can be combined flexibly according to the asset property and security requirements.
(3) The architecture proposed in this paper can provide a complete range of services. The service covers both regulated and competitive services, and can consider the local application of the user layer and the global application of the regional layer and the central layer.

6 Conclusion

This paper expands the concept of "horizontal integration, vertical penetration, and safety division" of the smart grid control system D5000, proposing an architecture system of "distribution self-discipline, centralized coordination, hierarchical partitioning, two-way interaction". Several key technologies for integrated energy management and service system are put forward including steady-state energy-flow integrated modeling and comprehensive decision-making based on hierarchical analysis. As a results, the comprehensive energy management and service system NIES5000 was developed, whose application in Project Tongli and others verified the flexibility, integrity and feasibility of the proposed key architecture and the ability to meet the overall needs of the service.

In addition, as a new technical direction, the integrated energy management and service system just start to develop. Therefore, there is still a lot of research and construction needs to be carried out, such as the online planning, online simulation for integrated energy, which has not been discussed within this paper.

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