Review of integrated energy system under deep integration of cyber-physical system

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Abstract. The safe and reliable operation of the integrated energy system (IES) under the deep integration of the cyber-physical system (CPS) relies on accurate modelling of information systems and energy systems. With the increasing requirements of the society on the operation of IES, it is very important to carry out corresponding modelling researches considering CPS. Firstly, this paper introduces the concepts of IES under deep integration of CPS. Secondly, the equivalent models for energy systems, information systems and integrated systems are pointed out, respectively. Finally, considering the correlation between information systems and energy systems, the future research directions of integrated cyber-physical energy systems are proposed.

1. Introduction

With the rapid development of renewable energy, computer technologies and internet technologies, the third industrial revolution represented by the integrated energy system (IES) is emerging [1]. In 2001, a plan was proposed by the U.S. Department of Energy to develop IES, aiming at promoting the spread and application of distributed energy systems and combined heat and power systems. This plan can increase the usage of clean energy [2]. European countries such as Germany and Denmark conducted researches on IES earlier. Germany launched the E-Energy project in 2008 to promote the efficiency of energy systems and the large-scale use of renewable energy. Advanced information technologies, communication technologies and market mechanisms were used in this project [3]. China also established several demonstration projects for IES. Beijing Yanqing Internet of Integrated Energy Demonstration Zone realized coordinated control of multiple energy sources which has improved users' quality and supply reliability [4]. Jiangsu Large-scale Source-grid-load Friendly Interaction System Demonstration Project actively promoted the effective implementation of Chinese energy supply-side structural reform [5].

With the rapid improvement of information technologies such as the Internet of Things, Big Data, and Mobile Internet, the deep integration of information systems and energy systems has been realized in IES. However, the number of measurement and decision-making units in IES has greatly increased,
more and more external information directly affects energy systems. The mechanism is getting increasingly complex between energy flow and information flow.

The safe and reliable operation of IES under the background of deep integration of the cyber-physical system (CPS) depends on the accurate modeling of information systems and energy systems. With the increasing demand of operation security of energy systems in society, it is more and more important to carry out the corresponding modeling researches on IES under deep integration of CPS. This paper first introduces the related concepts of IES under deep integration of CPS. Secondly, the corresponding models for energy systems, information systems and integrated systems are presented in turn. Finally, considering the relationship between information systems and energy systems, future research directions of IES under deep integration of CPS are proposed.

2. Conceptions of integrated energy system under the deep integration of cyber-physical system

IES is able to adjust the form of energy flow in the aspects of production capacity and energy consumption. This is accomplished through the conversion between different energy forms, such as storing electric energy as hydrogen energy or other forms of energy on the capacity side. Replacing electric energy with heat energy on the consuming side is also a way to change the form of energy flow [6].

Through the co-optimization of high-low heat energy and electric energy of generators, the efficiency of the combined cooling, heating and power production (CCHP) system has been improved greatly. Yu Xiaodan et al. considered CCHP as an integrated production-transmission-sales system which could optimize the generation, distribution, transmission, conversion, storage, consumption of the energy system in an automated way [6]. This system was mainly composed of energy supply networks (such as power supply, gas supply, cooling/heating supply networks), energy exchange links (such as CCHP units, generator sets, boilers, air conditioners, heat pumps), energy storage links (such as electricity storage, gas storage, heat storage, cold storage), terminal integrated energy supply units (such as microgrid) and a large number of end-users [7].

CPS is integrated with advanced information technologies and automatic control technologies such as sensing, computing, communication and control devices. Moreover, CPS is considered as a complex system, which could efficiently connect the computer, environment, information and user. Such system could optimize the distribution and usage of resource in an efficient way. CPS was defined as a multi-dimensional complex system which can be considered as an integration of computing, communication and physical environment [8]. It can promote the real-time perception, dynamic control and information service of large-scale engineering systems through the deep integration of computing, communication and control technologies [8].

The integration of IES and CPS is an irreversible trend. Therefore, IES is promoted with the combination of the characteristics of energy systems and cyber-physical systems. IES under deep integration of CPS can be defined as an evolving paradigm wherein energy carriers, such as electricity, thermal energy and fuel, can be brought together with highly advanced cyber infrastructures. These systems could maximize efficiency and minimize energy waste. The combination between information technologies and IES could strongly guarantee the security and optimization of energy systems’ operation and programming.

3. Modelling of energy system of IES under deep integration of cyber-physical system

CCHP is considered as one of the main forms of IES. In this system, wasted heat created by power generators can be used for heating and cooling task, which significantly raises the efficiency of the system. Kong Xiangqiang focused on the optimal energy management of CCHP consisting of a gas turbine, an absorption chiller and a heat boiler [9]. The optimization problem was modelled as a linear programming model to minimize the overall cost of energy for the CCHP system [9]. It was concluded that whether the load condition is satisfied plays an essential role in the optimal operation of the whole system [9]. The advantage of this model is its high feasibility which could guarantee a better performance compared to other complicated methods in simulation and shorten the calculating time. However, this simplicity may lead to a less ideal solution for the lack of accuracy in the process of modelling such a highly complex system [9]. In the literature [10], intrinsic parameters including total
energy utilization efficiency, equivalent energy efficiency et al. were discussed. It was found that economic exergy efficiency at off-design conditions can evaluate the optimal configuration and economic operation in two typical systems [10]. Outstanding progress was achieved including core technologies of thermal chemical complementarity of fossil fuels and solar energy, counter rotating ramjet et al., these achievements can firmly support the development of distributed energy in China [11].

IES should be able to combine multiple energy carriers such as electricity, natural gas, thermal energy. JIA Hongjie et al. discussed the general modelling of IES, as well as giving summary on reality and potential problem [12]. Energy hub (EH) is a promising concept for optimal management of IES [12]. The details of EH are shown in Fig.1 [12]. The conversion, distribution and storage of energy are done in EH, which divides energy load into electricity load, heat load and cooling load. EH could also effectively integrate demand side management into IES, which can earn great benefits for the system. Though a general modelling method was proposed, the method did not consider the static transfer and conversion relationship of different energy carriers as well as the uncertainty caused by the unpredictability from user side.

![Figure 1. Schematic diagram of EH [9,12]](image)

4. Modelling of information system of IES under deep integration of cyber-physical system

The power information system is a super-large-scale, wide-area distributed and hierarchically interconnected system. It consists of heterogeneous subsystems including dispatcher centers, power plants, and substation business systems. Ways to model information systems can be divided into several groups by the questions they focus on. HU Yan et al. proposed an abstract model of the power information system, security architecture design trace language, in order to describe the structure, business, user security strategy, potential attacks and feasible solution [13]. They designed the language to unify the description of systems. An automated risk analyzing algorithm was also proposed to obtain the attack trace of the information system [13]. Concept of relative security degree based on attack trace was given, which can give a quantitative assessment of the safety of information systems [13]. A telecontrol communication modeling method, which can be used on common data class, data set and report, was proposed to guarantee the interoperability between devices made by different manufacturers [14]. Meanwhile, models of logical devices, logical nodes and information exchange service were developed respectively to guarantee the efficiency of the whole model [14]. WANG Chao et al. analyzed the fundamental of relay protection in digital substation [15]. Information flow was divided into three kinds including synchronization flow, sampled value flow and generic object-oriented substation event flow [15]. Their topologies were then analyzed to calculate the connected rate considering redundant configuration with minimal path set in algorithm [15]. Moreover, a general reliability model of relay protection systems in digital substation was conducted [15].
modelling methods used to model information systems of the power systems can be used as a source of reference when modelling information systems of IES.

The characteristics of information systems were analyzed, and a structure of information and communication systems within IES was proposed [16]. Essential technologies including collecting information, processing, analyzing, security keeping and system supporting were also introduced to give a prospect on further researches [16]. In the literature [17], key applications in user side of IES and issues of communication network of user side were discussed. Simulation of information systems based on mininet and floodlight was also accomplished [17]. However, the details of advanced metering infrastructure and other modules were not analyzed, which could be improved later. CAO Junwei et al. mainly studied the information communication system technologies needed in IES [18]. They drew on the concept and concrete realization of the software-defined network (SDN), and pointed out that SDN can better meet the demand of information communication systems of IES under deep integration of CPS [18]. Traditional SDN was improved so that it could adapt to large-scale network [18]. Moreover, a model of communication systems was proposed with the combination of network routers and energy routers [18].

SUN Yi et al. combed the development of standardization, data models, structural systems and network processing mechanisms of energy efficiency bus (EEBus) [19]. They elaborated the smart premises interoperable neutral-message exchange (SPINE) and communication mechanism of EEBus [19]. Moreover, based on EEBus, the information interaction architecture of regional IES was designed, and the application of EEBus in IES were given [19]. The structure of EEBus is shown in Fig.2 [19]. Organizing layer could guarantee the efficiency of energy usage by choosing corresponding managing strategies. SPINE is set to define the data model in energy systems. Data communication protocols, including Smart Home IP (SHIP) and Thread, are used in information transporting layer to connect devices energy consuming layer. With EEBUS applied, the interaction within the generation-network-load-energy storage systems can be standardized, the system of reginal IES can be enriched and the initiative of participants of energy market (such as government department, electric power enterprises and auxiliary service providers) can be enhanced [19].

![Figure 2. frame of EEBus structure [19](image)](image)

5. Modelling of IES under deep integration of cyber-physical system

CPS is a complex system that involves not only discrete computational process, but also the process of continuous physical events. In the literature [20], existing modelling methods and tools
were introduced based on the characteristics of discrete systems and continuous systems. Numerous modelling methods were divided into 3 types including discrete modelling, continuous modelling and hybrid modelling [20].

Many modelling studies of CPS on the power system have been done. GUO Qinglai et al. abstracted the cyber-physical power system into directed graph [21]. Directed graph was composed of two parts: data nodes, which represents the state quantities in physical and cyber systems, and information branch, which represents data processing and transmission [21]. On this basis, the matrix operation method can quickly and simply perform quantitative calculation [21]. As connection strength and data transmission between nodes of two different networks were not taken into consideration in traditional methods, a more realistic unified modelling method considering secondary voltage control systems was proposed [22]. This method can be used in the calculation of modern large-scale smart systems [22]. In the literature [23], a hybrid modelling method based on finite state machine and mixed logical dynamical method was proposed in order to solve optimal control. Moreover, flexible load control and coordinated control of power source were modelled as well [23]. However, only the power system and its information system were taken into consideration in literatures above, deep integration of different energy forms was ignored more or less.

Based on the studies on the common structure of regional distributed energy systems (RDES), CHEN Juan et al. proposed an architectural model of RDES of CCHP based on multi-agent system (MAS), which provide a frame work for the deployment of RDES [24]. A structure of energy router and a model of cell in RDES were proposed on the basis of cellular automata theory, and a control strategy was given with combination of centralization and distribution [24]. Meanwhile, a comprehensive control strategy was proposed [24]. However, this model did not take uncertainty into consideration.

6. Prospect

With promotion of “Internet Plus” and “Industry 4.0”, it is inevitable to develop IES under deep integration of CPS. Such integration could maximize energy utilization efficiency through tight coupling between energy systems and information systems. Many researches have been conducted and approved on models of optimal operation, information security analysis and etc. This article provides some more views on future researches:

1) IES under deep integration of CPS is a temporal and spatial heterogeneous system, which means information data of different part of this system may not be measured and processed at the same time. Moreover, the response time of different kind of generation varies, which makes it hard to send commands to these generators synchronously. This characteristic makes it necessary to conduct more researches on models considering heterogeneity.

2) Recent researches on modelling IES under deep integration of CPS mostly were mostly concerned with static status, researchers did not look into the dynamic characteristics of whole system together with new subsystems like the hydrogen transport system. Therefore, it is necessary to develop new modelling and simulation platform for dynamic modelling.

3) Since a large amount of renewable energy sources are integrated in IES under deep integration of CPS, their uncertainty caused by weather factor may lead to heavy catastrophe. Therefore, more researches should be done to find a model considering this uncertainty.

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