Improved web-of-cells with characteristics of self-organized co-evolution and group intelligent decision-making: A novel perspective of smart energy dispatching

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ABSTRACT This paper proposes a novel perspective of smart energy dispatching based on the improved web-of-cells (iWoC) with characteristics of weak centralization, self-organized co-evolution and coupling, and group intelligent decision-making. The key technology concerning the dispatch and control of iWoC is investigated systematically for the first time, aiming to develop an intelligent scheduling system which has a high penetration of renewable energy resources. Based on practical engineering needs and iWoC which is characterized by self-organization, high independence, efficient synergy, and autonomous learning, a variety of advanced theoretical tools such as complex network theory, group machine learning (ML) and evolutionary game theory, have been adopted to address the following four basic scientific issues: the modeling method of self-organized coupled network of the cyber-physical-social systems (CPSS) based iWoC; the stability analysis and stability control system of the self-organized evolution of iWoC; a highly autonomous group intelligent decision-making method of an independent cell in the iWoC; multi-cells synergetic evolutionary game and group intelligent decision theory. Thus, an innovative breakthrough on intersection of complex network game theory and group ML is to be obtained, contributing to the emergence of group knowledge in complex system environment and a significant improvement in the level of group intelligent decision. Furthermore, software and hardware systems are designed and expected to be validated in the future on the practical smart distribution grid demonstration project which is undertaken by the authors. The biggest innovation of this paper lies in thoroughly investigating how to implement the overall optimal scheduling and control decision-making of a class of complex systems relying on massive group cells with characteristics of limited information, weak controllability, small capacity, and wide distribution.

INDEX TERMS improved web-of-cells, weak centralization, multi-agent systems, decentralized coordination control, self-organized co-evolution, complex networks, evolutionary game theory, cyber-physical-social systems, machine learning, artificial intelligence, smart energy dispatching

I. INTRODUCTION

With a rapid development of global distributed renewable energy resources in recent years, China has made remarkable achievements in the development of renewable energy. According to the new energy plan, the wind power and solar energy in China will reach more than 210 million kW and 110 million kW by 2020, respectively [1]. At present, China promotes the development of renewable energy through market means, and vigorously promotes the development of distributed energy via demonstration projects such as microgrids and new energy demonstration cities, ensuring that non-fossil energy accounts for 15% and 20% of primary energy consumption in 2020 and 2030, respectively. From a development perspective, the global energy structure is also
undergoing profound changes. In the future, global energy consumption will be dominated by renewable energy. The International Energy Agency (IEA) predicted that the proportion of global clean energy will exceed 30% in 2030 [2]. Moreover, an obvious crowding-out effect has been produced on traditional power supply due to a high permeability of the distributed generation (DG) with features of intermittency and random nature, thereby the global power systems are gradually confronted with a new challenging issue [3-7], i.e., what is the form of the dispatching and control system of electric power systems in the case of high penetration of DG participating in the free transactions of electricity market (EM) in the future?

To address it, many scholars have carried out a prospective work regarding this future scenario [5-16]. Since the marketing and social factors will remarkably enhance the complexity of the power systems, traditional power system analytical approaches and mentalities are difficult to be competent. Hence, it is essential to carry out basic investigation work from the perspective of complex systems.

In this paper, we try to answer this issue via proposing to carry out the investigation on self-organized co-evolution and group intelligent decision-making capabilities of new-type smart grid based on web-of-cells (WoC). We now briefly introduce the connotation and development process of WoC as follows.

In order to fully cope with the high penetration of renewable energy resources in power grids, a new hot research area has been formed on improving the capabilities of power systems to optimize, dispatch, and control DG. Further decentralization of energy management system (EMS) becomes the main solution. In particular, the EMS of traditional centralized-control power systems are allocated to the bottom layers of the distribution network.

In 2013, Zhang et al. [17] systematically proposed the EMS Family thought of decentralized autonomy and centralized collaboration for the power systems in the National 973 Project Study. We have proposed the concepts of territorial power grid and frequency autonomy in the National Natural Science Foundation of China (NSFC) in 2014. Subsequently, in 2015, the European Liaison on Electricity Committed Towards long-term Research Activity Integrated Research Programme (ELECTRA IRP) [3] put forward the concept of WoC and control scheme for the future (2035+) power system with high penetration of renewable energy resources. This conceptive WoC system is a completely new structure of power grid and also a forward-looking research result after long-term investigations on smart grid. It is proposed to enable the future power system to fully cope with the high degree of penetration of renewable energy in the power grid. Therefore, the precondition of this system construction is to predict the future development and change trend of the power grid through scenario hypothesis, which is also an important basis for this forward-looking system [18]. ELECTRA based on the investigation conducted by E-highway 2050 [19] has extracted seven uncontroversial development trends in the future power system as follows [20]: a) power generation will shift from classical dispatchable units to intermittent renewable energy; b) power generation will shift from few large units to many smaller units; c) power generation units will substantially shift from central transmission system connected generation to decentralized distribution system connected generation; d) electricity consumption will increase significantly; e) large amounts of fast reacting distributed resources can offer reserves capacity; f) electrical storage will be a cost-effective solution for offering ancillary services; and g) ubiquitous sensors will vastly increase the power system's observability. ELECTRA also deemed that [20] developments in information and communication technologies will support the pathway towards more decentralized managed power systems. The concept of WoC is presented by ELECTRA as graphically [20] in Figure 1.

Based on Figure 1, ELECTRA defines the cell in WoC [3-4]: it is a flexible combination of interconnected distributed generators, energy storage units and loads, within a certain range of power/geographical boundaries. In WoC, future power system (grid) will be divided into many smaller entities (geographical areas), i.e., cells, with local observability and control by a cell operator (CO) that is responsible for the real-time control of the cell. Among the cells, each one has autonomy, and the control relationship between them is equivalent. Therefore, local problems are solved locally in a secure manner, without system-wide communication, bottom-up aggregation and central decision making [20]. More importantly, the cells in the WoC system are connected with each other via tie-lines (one or multiple, radial or meshed), ensuring that neighboring cells can support each other in an autonomous distributed collaborative way and decide on local activation optimization [20]. In addition, ELECTRA proposed that [20] cells can contain/span multiple voltage levels; are dimensioned in relation to computational complexity of detection and resolution, sufficient reserves providing resources, etc.; and do not need to be self-reliant for matching demand with supply.
However, the concept of WoC proposed by the ELECTRA framework is still at stage of conceptual and technical framework. Actually, many new challenges have been put forward regarding WoC in the investigation of fundamental theory and specific technology.

In Figure 1, the primary system architecture of power system has not been changed substantially in the WoC system. However, it has a significant difference in mode of operation and idea of control. Therefore, compared to the currently decentralized WoC presented in Figure 1, based on the actual dispatching situations of the power grid, we propose an improved WoC (iWoC), i.e., the weak-centralized self-organized framework of WoC, which is presented as graphically in Figure 2.

Actually, many new challenges have been put forward regarding WoC in the investigation of fundamental theory and specific technology.

In Figure 2, the control structure of iWoC is more powerful than available centralized control systems in aspects of system orderliness, flexibility, extensibility, reusability, and compatibility. Therefore, iWoC is very consistent with the technical requirements of the new generation of power systems architecture, including widely interconnected, intelligent interaction, flexible and adaptable, safety and controllability, thereby it will be more suitable for new generation of energy and electric power systems with high penetration of DG.

Analogously, the cell in iWoC system is the smallest and autonomous unit or individual, so that the fully-distributed control and communication can be achieved through interaction between individuals, and interaction between individuals and the environment. This reveals some advantages of iWoC as follows [4]:

- **Self-organized property.** The global structure of iWoC is presented by the interaction between all cells. The interaction rules are only relied on the local information, instead of global information.
- **Highly autonomous property.** The control of iWoC is occasionally relied on central control, thus each cell in iWoC system has basically equal status, and the state of them does not directly affect the whole system.
- **High-efficiency collaboration property.** Each cell relies on limited information sharing and interaction between neighboring cells to achieve collaborative optimization, which is originally performed depending on the centralized control of a center.
- **Self-learning property.** The internal control of each cell is realized by feedback, so it has capabilities of adaptation and optimization.

Therefore, although the rules of each CO are simple, the iWoC system is a clusterability-based result of organizational effect and structural effect. Moreover, the higher the overall effect level, the more intelligence the group knowledge will emerge. The control idea of iWoC is designed to transform the intelligentization of power system into group intelligence, so as to provide a platform and an opportunity for the continuous emergence of group knowledge. Hence, it is of great significance to the development of smart grid and the research on utilization of renewable energy in the future.

iWoC is essentially a decentralized autonomous power grid in which massive and weakly-controllable DGs are dominant. Hence, the fundamental changes in power supply structure, system inertia, and information interaction are
bound to profoundly facilitate the transformation of traditional control modes of power systems [5]. Taking the power systems in China as an example, in the past, relying on the dispatching of dozens of large power plants, a provincial power grid is able to complete basic power balance and electricity balance control of the power system. Currently, after large-scale generation units are forced out by massive distributed power sources, especially massive DG system operators are participating in free market transactions, resulting in that the power balance and electricity balance of large-scale power grids need to be relied on massive and uncertain DG sources. This has become an enormous challenge in China.

Therefore, the construction and application of the intelligent control system in iWoC needs to tackle a series of dispatch optimization and decision-making issues after the weakly-centralized interconnection of cells in the iWoC. Among them, the core issue is how to implement decision-making of the overall optimal dispatch and control for a class of complex systems relying on massive group cells with limited information, weak controllability, small capacity, and wide distribution. To address it, we deem it is necessary to rely on cross-convergence of multiple disciplines and cutting-edge technologies, so that we can explore solutions to such problems from basic theoretical investigations, as shown in Figure 3.

![Figure 3](image-url)

**FIGURE 3.** The major relevant theories and technologies involved in exploration of the key scientific issues regarding iWoC in this paper.

Based on Figure 3, we aim to develop an intelligent dispatching system as ultimate goal in the context of high-permeability distributed renewable power supply. For the first time, we systematically put forward investigations regarding key technologies of dispatching and control for the iWoC proposed in this paper. With regard to technical characteristics of self-organization, high independence, high-efficiency collaboration, and self-directed learning of iWoC, together with its actual engineering demand, we adopt advanced theoretical approaches and mathematical tools such as cyber-physical-social systems (CPSS), complex network theory, group machine learning (ML), evolutionary game theory (EGT), and Internet-based Block Chain (IBC) [21-23] to concentrate on a critical issue: how to rely on the vast number of cells in the grid with features of limited information, weak controllability, small capacity, and wide distribution to realize the optimal dispatching and control decision in general for a category of complex system. Therefore, we systematically propose to investigate four key scientific issues as follows:

i) The modeling method of self-organized coupled network of the iWoC based on deep information integration of CPSS.

ii) The stability analysis and stability control system of the self-organized evolution of iWoC.

iii) A highly autonomous group intelligent decision-making method of an independent cell in the iWoC.

iv) Multi-cells synergetic evolutionary game and group intelligent decision theory.

On the basis above, we strive to seek innovative breakthroughs at the intersection of complex network game theory and collective ML, in order to generate emergence phenomena of group intelligence and group knowledge, noticeably improve the level of group intelligent decision-making in complex system circumstances, and develop and investigate system software and hardware, expecting that engineering verifications are able to be conducted in intelligent distribution network dispatch engineering demonstration projects.

In general, first, the proposal of iWoC conforms to the general trend of high-speed penetration rate of distributed renewable energy and online freed trading of large-scale DG at home and abroad, from the perspective of engineering innovation. The weak-centralization ideology of iWoC control system is consistent with the trend of decentralized-autonomy and centralized-collaboration of EMS, which is concentrated on by more and more scholars in recent years, while the technical requirements of iWoC are higher. We deem that the iWoC proposed based on WoC in this paper is an intuitive explanation for smart grids with broad interconnection, intelligent interaction, flexibility, security and controllability. There are four merits reflected in the dispatch and control system of iWoC, including self-organization, high independence, high-efficiency collaboration, and self-directed learning, which can be considered as a major upgrade to the framework of current smart grids characterized by centralized control centers.

Second, the core issue of iWoC intelligent control system in this paper is how to rely on mass group units (cells) with features of limited information, weak controllability, small capacity, and wide distribution to implement optimal dispatching and control decision-making on the whole for a class of typical complex systems (e.g., the multi-energy coupling comprehensive energy system), from the perspective of application of theoretical innovation. We deem that a series of dispatch optimization and decision issues need to be tackled for the construction and application of iWoC after weak centralization of multiple heterogeneous cells in the web.
In addition, we deem that we can further try to apply the investigation results of iWoC in this paper to intelligent distribution network dispatch demonstration projects in Guangdong Power Grid Corporation in the future, some of which are hosted by the authors currently. Therefore, the engineering reference value will be greater.

The major engineering value and scientific significance of this paper can be summarized as follows: first, we propose the concept of iWoC based on the ideology of conceptual WoC put forward by the ELECTRA in 2015. The core of iWoC is weak centralization, which is in accordance with the thought of emerging EMS with features of decentralized autonomy and centralized collaboration. However, the iWoC is more demanding. Four strengths are revealed in the dispatch and control system of iWoC proposed in this paper, including self-organization, high degree of independence, high-efficiency cooperatively, and autonomous learning, which can be seen as a very significant upgrade of current smart grid frameworks, which are characterized by integrated control center. Second, we first propose to use complex system theory, EGT, collective ML, and CPSS to solve the issues of optimal dispatching and control decision-making for a class of typical complex systems on the whole relying on massive cells in iWoC with characteristics of limited information, weak controllability, small capacity, and wide distribution. The investigation results in this respect have important theoretic reference value in the field of complex network theory, EGT, collective ML, and CPSS. Moreover, the investigation result in this paper can be applied in intelligent dispatching demonstration projects of distribution network hosted by the authors, indicating a significant engineering reference value in the future.

This paper is structured as follows: we first briefly depict related status and international developments in Section II. Subsequently, based on a variety of advanced theoretical tools, four basic scientific issues of the iWoC, i.e., the modeling method of self-organized coupled network of the CPSS based iWoC; the stability analysis and stability control system of the self-organized evolution of iWoC; a highly autonomous group intelligent decision-making method of an independent cell in the iWoC; and multi-cells synergetic evolutionary game and group intelligent decision theory, are thoroughly investigated in Section III, Section IV, Section V, and Section VI, respectively. Furthermore, some explorations on software and hardware systems development and engineering practice of the iWoC are carried out in Section VII. In Section VIII, we make a brief summary of the main contents in previous five sections as well as some prospects about the future research work on iWoC. Finally, Section IX concludes the main innovations of this paper.

II. RESEARCH STATUS AND INTERNATIONAL DEVELOPMENTS

In recent years, the technological development of smart grids at home and abroad has been further accelerated, which is mainly reflected in four aspects of power source, network, load, and energy storage. These four aspects are undergoing profound changes. In 2015, aiming at the future (2030+) power system with high penetration of renewable energy resources, ELECTRA proposed based on the scenario research conducted by E-highway 2050 [19] and extracted seventh incontrovertible development trends in the future power system [18–20]. Faced with a shift relationship between traditional and distributed power supply, how to effectively facilitate the massive interconnection of distributed power supply is an important part of the development strategy of various countries’ energy and power in recent years. ELECTRA proposed the concept of WoC for the first time for power systems that are highly permeated by renewable energy in the future. WoC is a new kind of smart grid architecture with thought of full decentralization. Based on WoC, the iWoC investigated in this paper is weakly centralized or not fully decentralized.

The weakly-centralized new dispatching and control architecture of iWoC can be regarded as entire systematization of micro-grid architecture. The emergence of this inspiration is not only driven by the actual demand for smart grid technology development, but also inextricably linked with latest research improvements in international community, such as the decentralization thought of IBC, ML technology, complex network theory and EGT, as demonstrated in Figure 3.

First, the concept of iWoC is high consistent with the technological development trend of decentralization concept of IBC. Under the impetus of Internet technologies, human communication has undergone profound changes. New communication and data analysis techniques have emerged in an endless stream. Power systems are also becoming truly digital power systems. Currently, big data and cloud computing technologies have gradually become a mainstream direction for the development of energy and electric power systems. Although the investigation on these technologies has extremely high requirements on dispatching operation data and communication security, the power departments throughout the world have been actively carrying out research work on how to use the open public Internet and multi-source data fusion methods to enhance the analysis capabilities of the system.

In recent years, the development of power system in China has also begun to accelerate rapidly in the direction of market-oriented reforms. With the tempting prospects of day-trading of power, incremental distribution network opening, distributed power supply online trading, and ancillary services of EM, the technology of IBC that combines Internet and market finance has begun to receive sufficient attention in the power industry [24]. The technology of IBC can be considered as a high-level form of big data technology and now has been developed into IBC 3.0 of decentralization in a wide application [25–26]. The idea of decentralization of IBC 3.0 coincides with the dispatching model of iWoC, but this is
definitely not a coincidence with a small probability. In our viewpoint, the decentralization of information system is an inevitable choice in the era of Industry 4.0. The idea of decentralized autonomy and centralized collaboration of the power system EMS proposed by Prof. B.M. Zhang [17] from Tsinghua University is essentially the same as that of iWoC. However, it must be pointed out that the weakening effect of the iWoC on traditional centralized control centers is much higher than that of new EMS architecture proposed in [17], and it is closer to the idea of decentralized IBC 3.0. Therefore, the technical challenges from iWoC are also more arduous.

Second, complex network theory [27-28] is a basic mathematical tool for analyzing self-organized iWoC. In the 1960s, Hungarian mathematicians Erdő and Rényi established Random Graph Theory [29], which was treated as the pioneering systematic research work of complex network theory in mathematics. Since the late 1990s, after Watts and Strogatz [30], Barabási [31] proposed the small world and scale-free network models in Nature and Science, respectively, the investigation on complex networks has entered an epoch-making research boom. Among them, the stability and synchronization of complex network topology has become one of its main research directions [32-40]. For many dynamic networks in real world, the failure of links or emergence of new links occurs in network from time to time, due to the links of nodes in the network are not always stable, and moreover, thus the structure of the network will change dramatically, and it is inevitable to fact switching between some different network topologies. For this reason, The Markov switching theory was proposed for the first time by Krasovskii and Lidskii in 1961 mathematically to describe the randomness of switching between different models [41].

In recent years, the dynamic analysis issues of complex networks with Markov switching features [42] have stimulated the interest of research in the international academic community. The application of this research in the social, biological, and engineering fields is in the ascendant. In addition, complex network theory has been used to investigate the issues of power grid, which is mainly focused on three aspects [43-48]: network structures, correlation between network structure and network performance, and comprehensive application. These have made important progress in topology modeling, cascading failure model, vulnerability analysis and key unit identification. The smart grid under the open EM is obviously a complex network. Therefore, it will be an inevitable trend to analyze issues of such a complex network based on complex network theory. This is a systematic theory that combines holism and reductionism, as the main mathematical analysis method. From the perspective of self-organized nature of iWoC, Markov switching dynamic network models can be used as a powerful mathematical tool for its network modeling. On this basis, Markov Decision Process (MDP) can also well solve related mathematical modeling issues of iWoC in ML.

Third, collective/group ML [49-51] is the key technology to solve the issue of self-directed learning of the control system of iWoC. ML is completed necessarily based on a good knowledge representation system. In the past 30 years, great progress has been made in ML [52]. The deficiencies in the traditional theoretical framework of ML are being gradually discovered and confirmed. Thereby, new theoretical frameworks for ML have been proposed [53-56]. In 2015, two papers [57-58] published by Google’s DeepMind team in Nature made the deep reinforcement learning become a hot topic in artificial intelligence (AI) community. Based on deep reinforcement learning method, a Go program, named AlphaGo, was developed by this team in 2016 and it broke the myth that Go cannot be simulated by AI. As a result, the deep learning as a perception based on multi-layer artificial neural network (ANN) and reinforcement learning as a decision based on MDP form a golden combination of ML [58-59]. In 2017, Wang et al. proposed a parallel learning theoretical framework based on the parallel system [54], in which a parallel virtual system is employed to generate a larger number of virtual samples for ML. In addition, generative adversarial network (GAN) [60-62] can be employed to automatically generate a large amount of simulation model data by constructing a max-min adversarial gaming system, which largely solves the problem of small samples in real circumstances. From AlphaGo [58], AlphaGo Zero [59], AlphaZero [63], parallel system [54, 64-65] to GAN [60-62], scholars have found ways to obtain sufficient data samples for ML. Obstacles that hinder the improvement of intelligence level of ML are gradually being removed. ML has been moved from the known training sample set (i.e., limited small data) to the new era of massive hypothetical training samples (i.e., unlimited big data) obtained via self-exploration, which will be a watershed for AI to surpass human intelligence. In the field of power systems, there was a research boom in the application of early ML such as back propagation neural network (BPNN), support vector machine (SVM), and fuzzy sets in the 1990s [66]. In the last two decades, the reinforcement learning algorithms [66-68] based on MDP as its rigorous mathematical foundation has become a new breakthrough in the field of ML. Among them, Q-learning [69], multi-agent correlated equilibrium Q(λ) learning, and adaptive dynamic programming (ADP), as well as other classical reinforcement learning algorithms have been introduced into the field of power system by the authors [70-76]. Lastly, the multi-agent EGT provides powerful mathematical analysis tool for analyzing interactions between cells in the iWoC system after implementing weak centralization. Game theory was formally adopted as a theory, beginning with the work Theory of Games and Economic Behavior by Von Neumann and Morgenstern in 1944 [77]. Nash then proposed and discussed the important concept of Nash equilibrium from 1950 to 1953 [78-81], which laid the theoretical foundation for non-cooperative games. Classical
game theory is based on three basic assumptions [82]: 1) players in the game are completely rational; 2) players have common knowledge; and 3) game structure and game environment are given in advance. Obviously, these assumptions are difficult to be satisfied in a complex system environment. In order to break the restrictions of the above three principles, Smith and Price introduced evolutionary ideas in biological theory into game theory, and published a creative paper The Logic of Animal Conflict [83] in 1973. This kind of game analysis methodology is originated from biological evolution theory, called evolutionary game theory (EGT), which is considered as a modeling method suitable for solving dynamic game issues in networks. In network groups, the transmission of information and the selection of strategies in evolutionary games can all be seen as the dynamics behavior on the network that obeys certain laws. How to characterize this dynamics behavior and discover the mechanism of it is the focus for researchers [84-87]. After EGT was put forward, it was quickly applied in many fields including power system. The relevant research work in power system is mainly concerned on the power economy fields [88-89] such as EM game behavior analysis, demand-side management, electricity price and investment, and power grid planning, etc. However, it is a pity that the game agents that have been investigated are mostly simpler two-party game issues. Furthermore, the WoC after conducting weak centralization will include a very complex multi-agent dynamic evolutionary game structure, thus the deep evolutionary game mechanisms, evolutionary game paths, and evolutionary game laws of iWoC will be very challenging, and meanwhile promising.

III. THE MODELING METHOD OF SELF-ORGANIZED COUPLED NETWORK OF THE CPSS BASED IWOC

Following contents are investigated in this section. First, we investigate the mathematical relationship between the self-organized behaviors of physical network, cyber network, and social network of iWoC and the coupling networks, in order to establish the mathematical model of Markov switching complex dynamic grid (MSCDG) that can be employed to describe frequent dynamic coupling and switching behaviors of the complex network. Second, we draw lessons from self-organized critical phenomena of the human and social group behavior, and conduct investigation on the influence of social factors on modeling of iWoC in the circumstances of EM, and further attempt to investigate the model of deeply integrating the existing cyber-physical system integration based modeling method of smart grids with social factors. Third, we investigate the GAN that is suitable for study of the self-organized evolutionary model of iWoC and try to build a parallel simulation system for iWoC based on the integration of CPSS. Lastly, through the integration of mathematical analysis approaches and simulation methods, we try to investigate the comprehensive modeling theory of cyber-physical-social self-organized coupling networks facing to iWoC. Specific investigation contents are presented as follows.


As illustrated in Figure 2, iWoC is mainly composed of three networks: a cyber-network, a power network (also called physical network), and a social network, thus iWoC is a typical cyber-physical-social system (CPSS) network. Based on this, we conceive a comprehensive iWoC. Its detailed structure is illustrated in Figure 4. Among this conception, the cyber-network is a secondary network which is composed of control and protection information flows. Nevertheless, the power network is a primary electric power network topology, in which multiple cells constitute a complete iWoC system, and each cell owns a transmission network and a distribution network inside. Therefore, this network integrates traditional power supply and DG, and is a multi-component independent network involving power source, network, load, and energy storage. The social network is a game network considering transactions in an open EM, which is constituted by the collaborative/competitive relationships between power dispatching decision terminals. Therefore, it is a relatively abstract social relation network. Moreover, this network is only partially dependent on the cyber-network, so that even if there is no communication and information exchange between cells in the iWoC, a game relationship can still be formed.

According to the state transition behaviors and interactions continuously occurred in the process of self-organizing and coupling in iWoC, we can use the MDP in random circumstances combining with network graph theory to establish its mathematical model. This switched complex dynamic network is a complex dynamics system network containing switching phenomena that arise during the evolving of the network topology structures or states of nodes. In addition, time-delay is a typical feature that exists in the transmission between nodes in the network, thus the time-delay is one of the major causes of network instability and poor performance. Due to the potential application value of Markov switching complex networks in the fields of secret communication, chemical and biological systems, information science and life science, it has become a hot spot with high investigation value. Obviously, the iWoC investigated and discussed in this paper fully possesses the above-mentioned characteristics. Therefore, the state transition and network switching phenomena in the complex dynamic network of iWoC can be characterized with the MDP or Markov chain. We call a class of dynamic networks with such kind of switching characteristic are a Markov
FIGURE 4. Idea drawing of cyber-physical-social system integration network structure of iWoC.

switching complex dynamic grid (MSCDG) [90-92]. The network dynamic equation of the iWoC can be depicted by the MSCDG based on the following steps.

Step 1: we establish a general mathematical model of complex network consisting of $N$ same dynamical systems which are regarded as nodes of the network. This model is described as

$$\dot{x}_i(t) = f(x_i(t)) + c \sum_{j=1}^{N} a_{ij} \Gamma x_j(t), \ i = 1, 2, \ldots, N$$  \hspace{1cm} (1)

where $i$ is the number of nodes in a network; $x_i(t)$ represents the state vector of the node $i$; $f(x_i(t))$ is a continuous vector-valued function; $\Gamma$ is an inner-coupling matrix; $c$ represents the strength of coupling; $A_{EC} = (a_{ij})$ represents an external-coupling matrix of the network topology structure, which is defined as follows: if there is a connection between node $i$ and node $j$, then it obtains $a_{ij} = a_{ji} > 0$, otherwise there is no connections between them and $a_{ij} = a_{ji} = 0$. Besides, the element on the coupling diagonal is defined as

$$a_{ij} = - \sum_{j=1, j \neq i}^{N} a_{ij}, \ i = 1, 2, \ldots, N \hspace{1cm} (2)$$

Step 2: we consider that the coupling nodes are non-linear in an actual network, thus there will necessarily be a complex network that is characterized by non-linear coupling. If we further consider that there is a switch function $r(t)$ between different models, thereby the classical complex network model presented in (1) will be transformed into a MSCDG model as

$$\dot{x}_i(t) = f(x_i(t), r(t)) + c \sum_{j=1}^{N} a_{ij} \Gamma x_j(t), \ i = 1, 2, \ldots, N \hspace{1cm} (3)$$

where $r(t)$ is the transition probability of Markov chain.

Step 3: we need to consider time-delay of this built MSCDG model, due to the speed of information input, transmission and processing is limited in complex network, resulting in a time-delay phenomenon in the network, which will easily lead to instability and performance deterioration of the network system. Thereby, the MSCDG considering time-delay is depicted as

$$\dot{x}_i(t) = f(x_i(t - \tau(t)), r(t)) + c \sum_{j=1}^{N} a_{ij} \Gamma x_j(t - \tau(t)) \hspace{1cm} (4)$$

where $\tau(t)$ is the time-varying delay; and $i = 1, 2, \ldots, N$.

In summary, the MSCDG model elaborated in the three steps above is characterized by continuous time, while such model is required to be a discrete-type one due to many control decisions of power grid are generally discrete in time in practice. Therefore, we can build a discrete-type MSCDG model for the case of discrete decision processes, which is demonstrated as

$$x_i(k+1) = f(x_i(k), r(k)) + c \sum_{j=1}^{N} a_{ij} r(k) \Gamma x_j(k) \hspace{1cm} (5)$$
Based on the MSCDG models elaborated above, a mathematical theory analysis can be conducted on the stability and synchronization of the networks in the process of self-organized evolution. The investigation on the stability or synchronization of iWoC based on the MSCDG models can be started from the following two aspects. First, starting from the dynamics behavior, we can investigate the stability or synchronization of the networks in order to give the judgment conditions. Second, starting from the network structure, we can judge the synchronization performance so as to improve the synchronization indexes. The investigation of network synchronization issues [93-94] is mainly based on Lyapunov stability theorem, synchronization manifold, matrix inequality, adaptive control and pinning control, etc., thereby some standards and criteria for determination of network stability or synchronization can be given.

In addition, due to the MDP is also based on Markov chain. Therefore, based on the MSCDG, we are also more convenient to carry out investigations on a class of MDP-based group reinforcement learning methods. The transition probability of the Markov chain, $r(t)$, in (3) can also be solved by the MDP method. This is another important reason why this paper adopts the MSCDG model.

### B. THE MODELING AND SIMULATION METHOD OF CPSS FOR THE GROUP DECISION-MAKING OF IWOC IN THE CONTEXT OF EM

In China, with a gradual liberalization of EM, in which participants have become more and more complex and diverse, not only including traditional power grid enterprises (PGEs) and electricity consumers, but also together with the emergence of a large number of emerging stakeholders, such as DG, energy storage, controllable load, and electric vehicle (EV), making the electricity trading in the competitive games of EM become more complex, diverse, and drastic, which is illustrated as graphically in Figure 5. These dispatching systems involved in the electricity trading can be seen as different intelligent decision-making agents, thus the group decision-making network formed in the competitive games can be modeled as a social network, which is illustrated in Figure 6 according to [95]. In the Figure 5, the power grid enterprise (PGE) group, new power supply entity (NPSE) group, and electricity consumer (EC) participating in a three-group asymmetric evolutionary game (AEG) in the EM, while the large-sized and small-sized generating corporation (GenCo) groups participating in a two-group AEG.

![Figure 5. Illustration of an open and ever-growing EM framework with complex, diverse, and drastic multi-group evolutionary games of electricity trading involving the groups of PGE, NPSE, and EC.](image)
Based on Figure 6, the modeling of MSCDG is a strict analytical mathematical method. However, for more complicated issues of social modeling, artificial experiment and simulation methods are more commonly used measures to address them, which are also called simulation methods. In 1990, Qian et al. [96] proposed a comprehensive integration method based on man-machine combination, indicating that complex system issues should be addressed via integrating expert group decision-making and intelligent information methods. On this basis, we believe that the following investigations need to be conducted: one aspect is study the influence of social and human factors on the modeling of iWoC in the circumstances of EM; the other is to investigate the mode and effect of deep integration between existing cyber-physical systems (CPS) fusion modeling approaches of smart grid and the social factors, so as to finally build a CPSS-based (i.e., tightly integrating social factors into the CPS) parallel simulation system for the iWoC. The specific framework of this parallel simulation system is designed as graphically in Figure 7.

In Figure 7, the designed whole control system framework is actually an extension of traditional control system and still composed of three parts that are elaborated as follows.

- **Part 1**: a generalized controller. Human dispatchers, who are regarded as executors of social factors, are integrated with comprehensive effects of the iWoC to constitute a generalized controller facing to the human and society.
- **Part 2**: a generalized controlled object (i.e., the parallel system). The closed-loop control system of the
physical iWoC system is combined with a parallel artificial system to form a generalized controlled object. Therefore, the generalized controlled object contains an actual system and a corresponding artificial system, and they constitute a parallel system. 

- Part 3: a generalized large-scale closed-loop feedback manager. The generalized large-scale closed-loop feedback is employed to evaluate the outputs of the entire parallel system, involving the causal changes in human and social attributes due to output control.

Based on the three parts above, in order to achieve the self-organized criticality phenomenon and emergence phenomenon generated in the complex system, it is essential to establish a mechanism that can produce complex dynamic states. For this purpose, this paper proposes to build a GAN [54, 97-99] to generate massive scenarios for the digital/physical mirrored simulation system, as illustrated in Figure 7. In this figure, based on GAN and its Monte Carlo simulation method, this simulation system is capable of automatically generating a large number of scenarios. Moreover, the statistical analysis methods are further applied to observe the self-organized criticality phenomenon and emergence phenomenon, which may occur in the self-organized behaviors of the iWoC, so as to lay a firm foundation for the emergence of group knowledge and group intelligence.

C. THE COMPREHENSIVE MODELING THEORY USED FOR THE CPS-S-BASED SELF-ORGANIZED COUPLING NETWORK OF IWOC

There is a class of stability analysis methods based on dynamics mathematical models, such as the transient energy function method [100] and the small signal stability method [101], that are very appropriate for studying the MSCDG-based network dynamics models proposed in this paper. Moreover, a more complete stability analysis theory has been built up in the MSCDG model based complex network theory system. Such stability analysis theory will be discussed in detail in next section.

Among such stability analysis methods introduced above, analogue simulation method is currently the most effective means to investigate the complex systems, especially the self-organized criticality phenomenon and emerging phenomenon of human and social behaviors. Therefore, we propose to integrate the analytical methods based on the mathematical model of MSCDG and the simulation methods based on parallel system for investigation in the future, thus the technical route will be relatively comprehensive, which will be conducive to the formation of a novel comprehensive self-organized coupling modeling theory with theoretically rigorous mathematical basis and applicability in engineering for the iWoC.

In this section, we have investigated three typical types of stability issues of iWoC:

1) Issues of complex network dynamics of the iWoC and evolutionary stability in the process of network topology evolution;
2) Issues of the evolutionary game stability of group decision-making of the iWoC in the complex circumstances of EM;
3) Issues of operational stability of the WoC in the complex scenarios generated by the GAN.

For the first type of stability issues above, which are issues of evolutionary stability for the nodes and branches of the CPSS network of iWoC on a long-time scale (e.g., month, quarter, and year), in a dynamic variation process of network structure and inner and external coupling modes. Therefore, the issues of network synchronization and network traction fall into this category, which are also basic issues commonly investigated in the field of complex network theory.

For the second type of stability issues, which are issues of searching for evolutionary stable equilibrium points on different time scales in a dynamic evolution process of mutual game relationships between different intelligent decision groups representing various cells or distributed equipment in the iWoC, in the complex circumstances of EM. These are also called stability issues of evolutionary game in the process of group decision-making in the field of game theory.

For the last type of stability issues, which are operational stability issues of the dynamic system in the sense of classical control theory and Lyapunov stability theory, i.e., the transient and static operational stability issues of the system on different time scales under various disturbances and complex scenarios. The well-known power system stability analysis generally refers to such operational stability. Based on this, the investigations in this section are elaborated as follows.

A. SELF-ORGANIZED EVOLUTIONARY STABILITY OF THE CPSS NETWORK OF IWOC BASED ON THE MSCDG NETWORK DYNAMICS MODEL

Research thought: we can first investigate specific issues and then general issues, or first study small-scale power grid models, and then large-scale ones. Specifically, first, we can select the IEEE standard examples that we are familiar with as well as the actual grid models that we have been established, including Hainan power grid, Shenzhen power grid, and Jiangsu Yancheng power grid models. Then, according to the idea of weak-centralization of the iWoC proposed in this paper, we can build a MSCDG-based iWoC model for the objective power grid.

Since we have established the MSCDG-based dynamic mathematical model in previous section, its stability can still be analyzed via adopting the Lyapunov’s first law and second law respectively. However, it is still difficult to directly deal with the non-linear functions in equations (1),
(3), and (4), such that we can only perform it in a small-scale and simple network. Therefore, currently, a more sophisticated way to address such issues is to convert the non-linear function into a linear equation via linearization for stability analysis, such that these issues can be transformed into the issues of eigenvalue analysis of a linear network equation. For a continuous MSCDG equation with time delays, we can transform it into a discrete model with control input after linearization and it is demonstrated as

\[ x_{r+1} = A(r)x_{r} + B(r)x_{r} + f(x_{r}) \]

\[ + C(r)x_{r} + g(x_{r-t_1})D(r)x_{r} + \sum_{i=1}^{n} h(x_{r-t_2}) + u(k) \]

where \( A, B, C \) and \( D \) are the Jacobian matrices of the non-linear function matrix after linearization; \( f(k) \) and \( g(k) \) are non-linear function vectors; \( r_{1} \) and \( r_{2} \) are time delays; \( u(k) \) is the control input matrix.

Therefore, based on the above linearization processing, we can design a generalized feedback controller, i.e., \( u(k) = K(r(k))x(k) \), via constructing a Lyapunov-Karsovaskii functional [102-105] which can be used to determine whether such networks reach stability and achieve synchronous regulation.

Based on (6), we can analyze the synchronization between different sub-networks coupled to each other as well as their traction method. For this purpose, we can adopt two methods for analysis: one is drive-response method and the other is continuous perturbation feedback synchronization method, which are introduced briefly as follows.

a) Drive-response method. In 1991, Pecora and Carroll [106] proposed that the MSCDG model can be further divided into two subsystems: the drive-type subsystem and the response-type subsystem (be driven). The former is a stable subsystem with negative Lyapunov exponents and the latter is an unstable subsystem with at least one negative Lyapunov exponent. Therefore, based on the coupling relationship between them, we can use the former as the latter’s drive (i.e., the controlled input), so as to draw the latter to reach a synchronous stable state. Kocarev and Parlitz [107-108] improved this drive-response method as active-passive method in 1995, and the principle of which is similar to the drive-response method.

b) Continuous perturbation feedback synchronization method. Pyragas [109-111] proposed that by continuously fine-adjusting the feedback coefficient \( K \) of the controlled input \( u(k) \), the synchronization of the aforementioned two sub-networks can be achieved, thereby realizing the control of continuous variable perturbation feedback for a non-linear continuous system.

As can be seen above, the selection and design of the generalized feedback controller designed in Figure 7 will be very interesting. Although this controller is not just a concept of controller adopted in conventional control theory, it also includes generalized control actions that can be used to perform external interferences (i.e., the tractions). For the characteristics of iWoC, it is clear that this direction can be explored with many useful concepts and strategies.

B. THE STABILITY OF EVOLUTIONARY GAMES IN THE PROCESS OF GROUP DECISION MAKING IN THE IWO Based on the MSCDG NETWORK DYNAMICS MODEL

EGT was first proposed by Maynard Smith [83] in 1973 when investigating the phenomenon of biological evolution. Unlike traditional game theory, EGT adopts the mechanism of natural selection without the need for strict rationality assumptions, making it closer to actual situations. There are some very important concepts commonly used in EGT, i.e., multi-group evolutionary stable strategy (MESS), replicator dynamics (RD), and asymptotically stable equilibrium point (ASEP). It is still possible to use the method elaborated in the previous section to construct the Lyapunov-Karsovaskii functional for discussing the evolutionary stability issues of group games. The authors have carried out some tentative investigations in this field, where we have studied the convergence of the multi-agent asymmetric evolutionary games in an open and ever-growing EM [95]. In particular, we analyzed the strategic convergence characteristics of multiple typical scenarios in the demand-side and generation-side EM. Figure 8 demonstrates the issues of evolutionary equilibrium stability and dynamic trend of evolutionary stable strategy (ESS) of the PGE group when they participate in time-of-use electricity pricing and electricity sales trading as the typical scenario of the demand-side EM illustrated in Figure 5.

![Figure 8](image-url)
The solid yellow arrows in the Figure 8(a) indicate a certain game situation and under which the phase trajectory of the PGE group is finally converged to the pure strategy \( S_{PG1} \) after a long-term evolution and development. This strategy \( S_{PG1} \) indicates that the PGE group chooses to cooperate with the NPSE group via providing a time-of-use electricity price \( P_i \) that allows the NPSE group to achieve more benefits. Figure 8(b) demonstrates another game situation and under which the PGE group finally evolve to the same stable pure strategy \( S_{PG1} \) with execution probability of \( x \).

Figure 8 also depicts that after a long-term evolution and development of the PGE group, the ultimate ESS developed in this group can resist any mutation strategy produced by other variation individuals to invade the group. Hence, all individuals in this group constantly imitate, train and learn from each other, so that the system will eventually achieve a dynamic equilibrium, called evolutionary stable equilibrium. In this equilibrium stable state, any individual will not be willing to change its strategy unilaterally, thus this equilibrium must be evolutionary/Nash equilibrium (actually it is a refined Nash equilibrium), and in which the PGE group can eventually achieve an evolutionary stable state.

When the number of agent or group involved in the multi-group evolutionary game is more, these evolutionary stability states produced by the evolutionary games in the group will be very complicated. To address it, traditional analytical methods are usually employed to convert the multi-agent stakeholders into solving of multiple two-two gaming issues. However, this is almost impossible to obtain the ideal Nash equilibrium solutions. Hence, traditional analytical methods have been difficult to solve such complex problems. This requires us to combine the simulative methods in more in-depth and systematic investigation work in the future.

C. OPERATING STABILITY ANALYSIS OF THE CYBER-PHYSICAL-SOCIAL INTEGRATION SYSTEM OF THE IWOC BASED ON GAN AND PARALLEL SYSTEM

The investigation on the occurrence of various self-organized critical phenomena and emergent phenomena in the complex systems described in this paper must be relied on massive simulations and statistical analysis. Therefore, with the help of parallel system and GAN, we propose to use the GAN of the self-organized evolutionary behavior of iWoC designed in Section III to construct a complex and diverse dynamic game circumstance for the iWoC, as illustrated in Figure 7. This idea can facilitate investigations of intelligent methods which are used to motivate the emergence of new group knowledge/intelligence and new phenomena in the complex systems, as well as self-organization evolution rules of the iWoC in a complex and random environment, such that contributing to the in-depth investigation of the guidance and stabilization effects of general pure strategy and mixed strategy in the stability of self-organizing evolution of the iWoC in a complicated environment.

Therefore, in this section, we need to introduce the mathematical statistics and analysis model as a mathematical tool to extend the conception in Figure 7 to the new ideas of big data analysis, which is illustrated as graphically in Figure 9, where we employ the GAN and parallel system to construct massive scenarios for mathematical analysis via two implementation stages as follows.

**Stage 1:** the stage of data processing. In this stage, first, we use the parallel learning method to select specific small data from actual physical raw data (e.g., the data of operational modes, system parameters, typical events, and dispatch and control system parameters) and artificial society model; second, we input these small data into the virtual artificial system to generate a large number of new data; lastly, we use these artificial data together with the specific raw small data to constitute the big data sets which will be learned for the issues we need to investigate and address. These big data sets after being learned can be used for updating the ML model.

**Stage 2:** the stage of action and learning. In this stage, we still follow the thought of MDP during the process of parallel learning. In other words, we use state transfer function to characterize the dynamic changes of the system during the process of learning from the synthetic big data, such that the knowledge that has been learned will be finally stored in the system state transfer function.

According to the role of the two stages elaborated above, we may need to add another stage, called Stage 3, into a complete process of parallel learning. This is because the iWoC proposed in this paper will be an open system, in which the artificial system we have constructed will also need to be open inevitably. Moreover, the change of raw data set and artificial system will also lead to a variation in the original data set. Therefore, we must add another stage into the theoretical framework of original two-stage parallel learning described in Figure 9. The Stage 3 is described as follows.

**Stage 3:** the stage of enhancement for the interactions between data and action. In this stage, data and actions are continuously kept reactivity and enhancement, which, in essence, can be regarded as a process of retaining and eliminating the big data sets.
As shown in Figure 9, the predictive learning and ensemble learning can be used to extend classical ML methods as follows:

- **Simultaneous learning of multiple robotic dispatchers.** Each of them as an agent who can independently obtain a series of observation data and take a series of actions to form a set, respectively.
- **For each robotic dispatcher, its obtained data and number and time of actions taken are independent.** Moreover, in the process of parallel learning, an action is allowed to generate multiple new data, besides, the data acquisition and action completion are performed in a very different frequency and order of occurrence.
- **A perspective of parallel world is adopted to observe the evolution of system states,** i.e., the newly acquired data is mapped into parallel space, and then the results of anticipatory actions are predicted and analyzed via mass and long-term simulation iterations, and the optimal action is eventually returned back to the real space.

Based on the above extensions, the coupling between data and action can be decreased and the existing reinforcement learning methods will be greatly extended, which can be seen as a result of employing individual robotic dispatcher to conduct medium and long-term simulation iterations for predicting and analyzing the anticipatory actions. In addition, the generations of data and action are relatively independent without time alignment. Hence, this is a typical realization process from actual small data to virtual big data. In fact, the above three extensions have been fully embodied in AlphaGo [57-59]. Based on the framework of parallel ML presented in Figure 9, the independent ML ability of individual robotic dispatcher in a centralized dispatching manner can be greatly improved. As demonstrated graphically in Figure 10, the principle of parallel ML for individual robotic dispatcher can also be visually explained by the Data/Action diagram of AlphaGo.

In Figure 10, the parallel world can be viewed as an integration of data sets and action sets, and while, multiple virtual parallel worlds are generated via the virtual artificial parallel system (VAPS). In the parallel learning system of robotic dispatcher, the data in the real world can be mapped to the parallel world (i.e., the real existing operation states) which is generated by the VAPS, and then a multi-line iteration approach can be adopted to calculate various possibilities that the real world evolves into other parallel worlds, mathematically, i.e., the possibilities that the current state transfers to other states. In this process, the decision-making of each step is evaluated by reinforcement learning algorithms (e.g., ADP, Q-learning), such that the action with highest reward is chosen for decision (i.e., a MDP). In addition, the ensemble learning in Figure 9 is suitable for ML of group robotic dispatchers, which contains mechanisms of multi-agent dispersed learning and collaborative learning.

As stated previously in [54] and [64], Wang proposed a detailed basic framework of parallel learning and the concept of ACP (i.e., artificial society, computational experiments, and parallel execution). On this basis, and according to Figure 7, Figure 9 and Figure 10, we can design a parallel control execution framework for the virtuality-reality interactions between virtual worlds and real words based on the robotic or human dispatchers, as illustrated in Figure 11.

**D. FRAMEWORK INVESTIGATION OF THE DISPATCHING AND STABILITY CONTROL SYSTEM OF THE IWOC**

The stability analysis in this section will lay a solid foundation for design of the overall framework of the dispatching and stability control system of the iWoC. In a traditional power system with a centralized control mode, its stability control framework in general is a hierarchical and radial control system architecture which is centered on the dispatching departments at all levels. However, the iWoC in this paper possesses a new type of weakly-centralized dispatching and control system which is highly independent and reliant on limited boundary information. Table I demonstrates a kind of control architecture for the dispatch and control system of iWoC. This architecture is originally proposed and recommended for the WoC presented in [18-20]. In Table I, the system control architecture of the iWoC still follows the traditional hierarchical control mode. However, since each cell in the iWoC system needs to communicate and coordinate with the neighboring cell/cells, resulting in the specific content of each level will change accordingly. As depicted in Table I, apart from primary voltage control (PVC) and pose-primary voltage control (PPVC), there are four levels, including Level 1: inertia frequency control (IFC), Level 2: frequency containment control (FCC), Level 3: balance restoration control (BRC), and Level 4: balance steering control (BSC). Therefore, the voltage control and frequency control of the WoC system are briefly introduced according to [18-20] as follows.

<table>
<thead>
<tr>
<th>Number</th>
<th>Function</th>
<th>Level</th>
<th>Voltage/frequency control mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Voltage</td>
<td>/</td>
<td>PVC</td>
</tr>
</tbody>
</table>
Cyber connection

Teleindication

Information system

Cyber connection

Thermal plant

Cyber connection

C

S

Teleadjusting

A:

Data

Frequency

the system

regulation

voltage of

dispatching system

units to a large number of distributed energy and renewable

have been changed from traditional large-scale generating

resources used for voltage control in the PVC of this system

not been changed substantially, except the fact that the

primary voltage control) of WoC presented in Figure 12 has

voltage control structure, the voltage control mode (i.e., the

is illustrated in Figure 12. Compared with traditional primary

In addition, the action time of PVC is very short and it is
generally millisecond grade, thus we can realize automatic
regulation through automatic voltage control (AVC). The

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security and economy of internal areas of the cell, thus the functions of traditional secondary voltage control and three-time voltage control have been integrated in PPVC.  

(2) Frequency control of the WoC system

The overall framework of the frequency control of the WoC system is illustrated in Figure 13. Compared with traditional three-time frequency regulation and control, the function of IFC has been added into the WoC system, which is equivalent to reestablishment of a relationship between the rotational speed of electric generator and the grid frequency, so that the hidden inertia of the system can be released via the control of power electronics at the first time once the frequency is unstable. As shown in Table I, the four levels of frequency control are briefly introduced as follows.

**FIGURE 13.** The overall framework of frequency regulation and control designed in the WoC system that is proposed by the ELECTRA.

**Level 1:** this level is IFC, and its purpose is to make the rate of change of frequency (ROCOF) of the system not exceeds the maximum allowed. The CO monitors the inertia reserve of power generating units or loads. Thereby, according to the frequency deviation and ROCOF of the system, an activation scheme for the inertia reserve capacity can be determined. Then, this activation scheme is implemented by the IFC in order to realize the regulation of the ROCOF of the system. At this point, the IFC is usually employed to coordinate with the FCC so as to improve the transient stability of the whole system.

**Level 2:** this level is FCC, and its goal is consistent with the goal of conventional primary frequency control, i.e., utilize the inherent load frequency characteristics of the system and the speed controller effect of generating unit to effectively avoid the system frequency deviations from exceeding the allowable range, such that FCC is capable of rapidly regulate the system frequency deviation to the greatest extent. The major difference between FCC and traditional primary frequency regulation is that the capacity used for frequency regulation via FCC has been changed from traditional generating unit to DG cell and renewable energy source. However, due to the intermittency, randomness, and volatility characteristics of renewable energy source, the frequency fluctuation will occur frequently, thus the requirements of rapidity and sensitivity for the FCC are also higher.

**Level 3:** this level is BRC. Its goal is similar to traditional secondary frequency regulation, i.e., the internal power balance of the cell is recovered via regulating the power flow in the cell. Normally, the traditional secondary frequency regulation is implemented for the provincial large-scale power grids, and the performance indexes are the index system of control performance standard (i.e., the CPS1 and CPS2). However, the BRC not only completes the secondary adjustment of the system frequency, but also needs to regulate the power flow in the cells so as to restore its internal power balance and the power exchange error of the connection line between the cells in the WoC system. The regulation of BRC is implemented in the cells, which is considered as the core of autonomy for the cells. At this point, the resources used for balance control are originated from the generating units, loads and energy storage units in the cell. In addition, the implementation of BRC is only based on local information and completed inside the cell. In order to achieve global optimization of the system, we need the next level (i.e., the Level 4) to complete this goal.

**Level 4:** this level is BSC. It is an important link to achieve mutual coordination and cooperation between adjacent cells in the iWoC system. The first goal of BSC is to prevent potential accidents through short-term predictions, and the second is to replace the BRC decision with BSC decision so as to achieve economic optimization.

Obviously, from the perspective of complex network theory and smart dispatching, there are still many aspects that are worth discussing and improving for the control structure presented in Table I. For example, Table I does not include contents regarding how to conduct network traction and game strategy guidance. This is why the concept of WoC needs to be extended as iWoC in this paper, instead of directly and simply copying its concept and framework which are proposed by the ELECTRA [19-20].

Based on stability analysis of the complex systems, we deem that the control architecture of WoC proposed by the ELECTRA should be further integrated with the investigations in this paper. In addition, we should draw on the security and stability control structure of the three lines of defense in the traditional power systems, thus we can effectively investigate the coordination framework involving transient stability control, static stability control, and dynamic stability control, and finally form a new system architecture that is truly feasible in engineering for the optimal dispatching and stability control of the iWoC. This will also lay a firm foundation for the investigation of the group intelligent decision system of iWoC in next Section V and Section VI.

**V. A HIGHLY AUTONOMOUS GROUP INTELLIGENT DECISION-MAKING METHOD OF AN INDEPENDENT CELL IN THE IWOC SYSTEM**

In this section, we will investigate the intelligent decision theory and method of different types of highly autonomous
groups in the independent cell of the iWoC system. The cell here is an independent unit in the iWoC system. There is a considerable difference between the cells with different levels of voltage, which reflects that the compositions of power source, network, load and stored energy within the cell are quite different, and the participation degrees of them in dispatching and control of the power grid are pretty different as well. Therefore, based on this, we conduct investigations on the independent cells across two dimensions, i.e., one is the dimension of voltage level, and the other is the dimension of system state. In the former dimension, we need to carry out investigations on group intelligent decision theory for different types of independent cells in the iWoC system, such as the high-voltage level of cell (i.e., transmission network), medium-voltage level of cell (i.e., transmission/distribution network), and low-voltage level of cell (i.e., distribution network). In the latter dimension, the investigation of group intelligent decision theory should be focused on solving some key issues due to high degree of autonomy possessed by the independent cells in the iWoC system. The major issues are the coordination of voltage, frequency and inertia between the autonomous cells. Based on the two dimensions above, specific research contents of this section are elaborated as follows.

A. INDEPENDENT CELL GROUP INTELLIGENT DECISION THEORY FOR FREQUENCY AUTONOMY

We have conducted in-depth investigations on group intelligent decision theory for the frequency control and automatic generation control (AGC) system. However, these previous investigations are generally based on conventional power supply structures, which are mainly composed of hydro-power generating units and thermal generating units. During the investigation, although we have considered the participation of DGs and EVs in frequency control of power network, we did not conduct this investigation in accordance with the structure of DG with high degree of penetration, nor did we considered the system inertia, as well as the influence of social behavior factors of various agents participating in frequency regulation in the cell. Based on previous research work, we can continue to conduct further investigations in this direction elaborated above as follows.

First, for the high-voltage level of cells, their frequency control strategies can still follow the traditional control strategies. It is well known that the power grids with high-voltage levels are generally transmission grids, while traditional large-scale generating units such as hydropower, thermal, nuclear, gas and pumped-storage are directly connected to the power grids with 220/500kV voltage level. The primary frequency regulation and AGC on which traditional frequency control relies are both implemented with these large-scale generating units. For high-voltage cells, there is generally no self-organized coupling phenomenon occurred in these cells, due to that the connections of large-scale power plants to the grid are strictly in accordance with the approval. Therefore, such high-voltage level of cell is still considered as a simple system.

For medium-voltage and low-voltage levels of cells, where a large number of renewable power sources, energy storage equipment and loads participate in frequency regulation of power network. Moreover, during this regulation, random self-organized coupling phenomenon occurs, thus such cells are the research highlights in this paper.

According to the structures of power source, network, load and energy storage, and based on the method elaborated in Section III, the self-organized coupling network with cyber-physical-social integration can be established for the medium- and low-voltage cells. In recent years, we have carried out fruitful investigation in this direction [74, 95, 112]. Concretely, we have adopted a wolf pack hunting algorithm to achieve group intelligent decisions for the frequency control of a distribution network [74]. In addition, we have used the lifelong learning method to realize complementary generation control of interconnected power grids with high-penetration renewables and EVs [112].

The following is a brief introduction to a concrete example that explains how to use a complex network model and a CPSS-based parallel learning architecture to design a support system for group intelligent decision making.

In this example, we have adopted complex network theory to conduct CPSS modeling of a micro-grid. Addressed concretely, we adopt the parallel ML method to implement the group intelligent dispatching decision-making during the process of third-time frequency regulation of the system. The architecture of CPSS integration in this example is illustrated in Figure 14.
In Figure 14, the distributed energy management (DEM) system is the energy center of the typical micro-grid, and the designed social system adopts a complex social network model in the social space, which is established based on consensus collaboration strategy and correlated equilibrium (CE) game strategy. In addition, it can be seen that the cyber space (C) is a bridge or link between the social space (S) and physical space (P).

In addition, the CE in Figure 14 is reflected in a general game model in the game theory, in which a CE is more general than a Nash equilibrium as the set of Nash equilibria is completely included in the set of correlated equilibria [113]. Obviously, a CE can also be regarded as a Nash equilibrium under a special condition. Generally speaking, a CE is a probability distribution of joint actions from which no agent or no cell is motivated to deviate unilaterally, which can be combined with Q-learning, as follows:

\[
L_{k} = \prod_{\alpha \in A_{l}} \pi_{l}(a_{l}) = \prod_{\alpha \in A_{l}} a_{l} \neq a_{l}
\]

where \(\pi_{l}\) is the probability distribution of state-action of the \(l\)th decision agent, which can be called a CE only when it satisfies the inequality constraint in (7); \(Q^{k}\) is the knowledge matrix of the \(l\)th decision agent at the \(k\)th iteration, which represents the knowledge values of state-action pairs; \(s_{k}\) is the state of the multi-agent system at the \(k\)th iteration; \(\bar{a} = [a_{1}, \ldots, a_{l}, \ldots, a_{l}]\) is the joint action of all the decision agents; \(a_{l}\) is the action of the \(l\)th decision agent; \(L\) is the number of the agents; \(\bar{a}_{l}\) is the joint action of all the decision agents except the \(l\)th decision agent; \(A(s_{k})\) is the agents' set of available joint actions in state \(s_{k}\); \(A_{l}\) is the \(l\)th decision agent's set of pure actions; and \(a_{l}^\alpha\) is the \(l\)th decision agent's any other action except the action \(a_{l}\).

Based on (7), we can adopt a novel group reinforcement learning method, called CE-Q learning to complete the seeking process of CE presented in (7). This is a knowledge learning process, during which each cell, according to the state-action-reward-state data via continuous interactions with the environment, can update its own knowledge of different state-action pairs with the feedback rewards by reinforcement learning. In this paper, we propose to use Q-learning [114] to achieve this learning process, such that we can store the group knowledge via the Q-value matrix, as follows [115]:

\[
V_{l}(s_{k+1}) = \sum_{s_{k} \in A_{k}} \pi_{l}(s_{k+1}, \bar{a}) Q^{k}_{l}(s_{k+1}, \bar{a})
\]

\[
Q^{k+1}_{l}(s_{k}, \bar{a}) = Q^{k}_{l}(s_{k}, \bar{a}) + \gamma \left[ (1 - \gamma) R_{l}(s_{k}, \bar{a}) + \gamma V_{l}(s_{k+1}) - Q^{k}_{l}(s_{k}, \bar{a}) \right]
\]

where \(V(s_{k+1})\) represents the state value-function of the \(l\)th decision agent in state \(s_{k+1}\); \(\alpha\) is the knowledge learning factor; \(\gamma\) is the discount factor; \(R_{l}(s_{l}, \bar{a})\) is the feedback reward after implementing a joint decision-making action \(\bar{a}\) under state \(s_{l}\).

Based on above descriptions, we can obtain the statistical results of the third-time frequency control optimization for a typical testing system. The statistical results indicate that the parallel learning system using the CPSS structure can be well employed to complete the tasks of group intelligent decision-making. In addition, this learning system not only has a high-speed convergence, but also possesses the capability of online learning, ensuring that the system remains adaptable sufficiently in a complex and ever-changing environment.

B. GROUP INTELLIGENT DECISION THEORY FOR THE GROUP OF INDEPENDENT CELLS IN AUTONOMOUS VOLTAGE CONTROL

As stated in Section IV, the issues of autonomous voltage control for the iWoC systems are relatively simpler than their frequency autonomy. This is because the voltage control is originally conducted based on local balance, and what it needs to solve is how to achieve a global optimization effect of reactive power based on limited boundary information and decentralized optimization algorithms in the case of complex network changes. There have been some investigations regarding the network partitioning and subtasks decomposition for an optimization issue of the complex power system. In addition, we also have a good accumulation of decentralized optimization algorithms. Therefore, what need to be investigated in depth are multi-agent evolutionary game and its group intelligent decision theory and method for an open reactive power regulation auxiliary service market. Therefore, we can still carry out relevant investigations in the same way as the previous section on frequency autonomy, which is not repeated here.

C. GROUP INTELLIGENT DECISION THEORY FOR THE GROUP OF INDEPENDENT CELLS IN COORDINATION OF VOLTAGE, FREQUENCY AND INERTIA

The internal of a cell in the iWoC is a multi-agent complex system consisting of power source, network, load, and energy storage, especially when the DGs with a high penetration are connected by inverters. At this point, the cell must be relied on DGs to implement stability control of frequency, voltage and power angle simultaneously. Therefore, obviously, the frequency of system, the node voltage and the virtual inertia are very difficult to be decoupled.

Regarding the complex issues of general multi-agent games involving multi-objective coordination and control, the Nash game combined with Pareto multi-objective optimization is a commonly used method to solve these multi-agent game issues. Addressed concretely, we first obtain the Pareto frontier of each decision agent. Then, we use the Pareto frontier of each agent as inputs to form a Nash equilibrium function. Lastly, we solve the Nash equilibrium point of this Nash equilibrium function, which can be called a Nash-Pareto solution. This solution is usually unique, ensuring that the results are win-win for the agents. We have used this method to solve an interactive game among diverse multiple household users and a distribution network in [116].
The obtained results show that the minimum target of peak-to-valley difference and network loss of the grid can be achieved. In addition, the user’s electricity consumption comfort and economy goals can also be achieved. Therefore, in this section, we can still adopt the complex network theory, game theory and parallel ML to investigate the group intelligent decision of the group of independent cells in the coordination of voltage, frequency and inertia. Specific procedures are elaborated as follows.

First, we should address the dynamic issues of network branches. The switching action of all the lines, information links and social relationships inside a cell can be considered as dynamic changes of branches in the network. For the established MSCDG network dynamics model, we can combine evolutionary game with the optimization problems. Hence, as described in Section III and Section IV, we can transform the self-organized coupling process of the cyber-physical-social network topology of iWoC into an evolutionary game issue, such that the game equilibrium functions such as Nash equilibrium and CE functions can be transformed into a solving problem of Pareto optimization objective function, in which the dynamic behaviors of network topology can be incorporated into the optimization decision.

Second, we should address dynamic issues of network nodes. The DG, energy storage and loads all can be regarded as dynamic changes of the nodes in the network. Hence, we can still combine the Nash game with Pareto multi-objective optimization to solve this dynamic issue. During the process, the controllable equipment of each node is treated as an agent participating in the game, and each agent’s own Pareto frontier can be determined separately. At this point, the entire cell is regarded as an agent, then we can obtain another Pareto frontier based on the targets of global frequency, reactive power and inertial of the whole system. Based on this, the issue to be solved in this section will be transformed into a Nash game issue between system agent and multiple distributed equipment agents. In the process of solving this issue, all the Pareto frontiers are considered as inputs of the Nash game optimization function. Finally, we can obtain a Nash-Pareto solution that is satisfied both by the system and the distributed equipment. Generally, the optimization issue of complex systems is difficult to be satisfied with non-convex conditions, thus we can use the methods such as NSGA-II [117], SPEA2 [118], and MGSO [119] to search the Pareto frontier.

Third, we should integrate the two optimization decision-making issue of network branch dynamics and node dynamics described in above two procedures. Actually, it is necessary to determine whether need to split the topology and the node into two sub-problems to be solved, or form a unified optimization model to solve the problem, which depends on the size of the independent cell to be investigated in the iWoC system.

Lastly, the above optimization decision making and solving process is used as the dispatching system of the mirrored virtual artificial parallel system (Figure 7). Then, use the GAN to automatically generate massive scenarios. In these scenarios, through the offline calculation, a parallel ML-based sample data generating system can be constituted to promote the emergence of group decision knowledge, such that we can achieve group intelligent decision making in the complex environments via ML methods.

It should be particularly pointed out that if we do not rely on the parallel ML system, and in contrast we directly adopt the above method for the dispatching and control decision making of the actual iWoC system, thus the computational complexity will increase exponentially with the changing of network topology structure and the increasing of the number of decision agents and optimization objectives. In addition, the time consumed in strategy solving will be difficult to meet the time requirements of real-time control of voltage/frequency/inertia of the iWoC system. In contrast, although the offline parallel ML is very time-consuming, once the pre-learning is completed, the speed of intelligent decision making will be very fast. This is also the biggest advantage of well-known AI systems.

VI. MULTI-CELLS SYNERGETIC EVOLUTIONARY GAME AND GROUP INTELLIGENT DECISION THEORY FROM A SYSTEM-WIDE PERSPECTIVE

In this section, we conducted investigations from a system-wide perspective, which aim at the issues of group intelligent decision making under the circumstances that various highly-autonomous cells are widely interconnected in the iWoC system. On this basis, two key issues have been discussed in this Section VI as follows:

- **Issue 1**: the issue of master-slave games (e.g., Stackelberg game) and group intelligent decision-making for an interconnected system consisting of multiple cells in different positions.
- **Issue 2**: the issue of hybrid games and group intelligent decision-making for an interconnected system consisting of multiple cells with equal positions.

Obviously, it is seen from the two issues that there is a global and local correspondence between this section and the previous section. In addition, analogously, there is a close correlation like a relationship between an entire system and a subsystem among the group intelligent decision-making systems elaborated in this section and the precious section. Based on the two issues above, specific contents in this section are elaborated as follows.

A. MASTER-SLAVE GAMES AND GROUP INTELLIGENT DECISION-MAKINGS AMONG AN INTERCONNECTED SYSTEM CONSISTING OF MULTIPLE CELLS WITH DIFFERENT POSITIONS

The iWoC proposed in this paper is a weakly-centralized advanced form of smart grid. However, the operation characteristics of actual power systems determine that such
weak centralization feature is not equal to absolute decentralization, indicating that the dispatching positions of regional grids and each provincial grid are still very important in the iWoC system. Therefore, from a system-wide perspective, although a high degree of autonomy is emphasized in the iWoC, the cell operators (COs) with different voltage levels and different functional roles still have an asymmetrical relationship, called master-slave game relationship. In this regard, we propose that we can use Stackelberg game equilibrium to depict such master-slave game relationship between upper and lower cells in the iWoC system in this section, as follows:

$\begin{align*}
\left( \bar{\mathbf{x}}^*, \bar{\mathbf{r}}^* \right) &= \arg\max_{\mathbf{x}_m \in A_m} U_{\text{leader}} (\mathbf{x}_m, \bar{\mathbf{x}}^*), \quad \text{for the leader} \\
\bar{\mathbf{x}}^*_m &= \arg\max_{\mathbf{x}_m \in A_m} U_m (\bar{\mathbf{x}}^*, \mathbf{x}_m), \quad \text{for the follower } m
\end{align*}$

subject to

$\mathbf{r}^* = (\bar{\mathbf{r}}_1^*, \ldots, \bar{\mathbf{r}}_m^*)$

where $\mathbf{r}^*$ represents the $m$th follower in a Stackelberg game, and $m = 1, 2, \ldots, M$; $M$ is the total number of followers; $\bar{\mathbf{r}}^*_m$ is the current optimal strategy of the leader; $\bar{\mathbf{r}}^*$ is the joint optimal strategy of all followers; $\bar{\mathbf{r}}^*_m$ is the current optimal strategy of the $m$th follower; $U_{\text{leader}}$ and $U_m$ are the payoff functions of the leader and the $m$th follower, respectively; $A_{\text{leader}}$ and $A_m$ are the decision-searching space of the leader and the $m$th follower, respectively. Based on (10), then we can use the methods of group Q-learning and transfer learning to form a fast Stackelberg equilibrium learning (FSEL) based group intelligent decision-making approach. In this approach, the Q-learning expression is presented as follows:

$\begin{align*}
Q_{m, t}^{x_{m, k}^*(s_{m, k}^*, a_{m, k}^*)} &= Q_{m, t}^{x_{m, k}^*}(s_{m, k}^*, a_{m, k}^*) + \alpha \cdot \Delta Q_{m, t}^{x_{m, k}^*} \\
\Delta Q_{m, t}^{x_{m, k}^*} &= R_{m, t}^{x_{m, k}^*}(s_{m, k}^*, a_{m, k}^*) + \gamma \cdot \max_{a_{m, k+1}^*} Q_{m, t+1}^{x_{m, k+1, k}^*}(s_{m, k+1, k}^*, a_{m, k+1}^*) \\
Q_{m, t}^{x_{m, k}^*} &= \arg\max_{a_{m, k}} Q_{m, t}^{x_{m, k}^*}(s_{m, k}^*, a_{m, k}), \quad \text{if } q_{m, k}^* \leq \varepsilon \\
&= \text{ otherwise}
\end{align*}$

where $m = 1, 2, \ldots, M$; $t = 1, 2, \ldots, T_m$; $T_m$ is the total number of followers who have interaction with follower $m$; $q = 1, 2, \ldots, Q_L$, and $Q_L$ is the total number of real code for transfer learning of follower $m$; $p = 1, 2, \ldots, P_S$, and $P_S$ is the total number of searching of follower $m$; and the relevant symbols have been defined in (7)–(11). It should be added that the superscripts $q, p$ and $k$ represent the $q$th real code for transfer learning, the $p$th search, and the $k$th iteration, respectively; $R_{m, t}^{x_{m, k}^*}$ is an immediate feedback reward, which can generally be transformed from the optimal objective; $Q_{m, t}^{x_{m, k}^*}$ and $\Delta Q_{m, t}^{x_{m, k}^*}$ are the knowledge matrix and its increment, respectively; $q_{m, k}^*$ is a random value in the unified probability distribution; $\varepsilon$ is a parameter of local greedy searching; $a_{\text{rand}}$ represents the global random searching action.

This approach expounded above can be extended to solving the issues of master-slave gaming in multiple autonomous cells. We have conducted a preliminary investigation on this in 2017. Among this, we have employed this approach to secondary frequency control of a power grid in an integrated energy system (IES) considering multi-energy integration. Concretely, we have taken the Hainan Power Grid as an example for analysis, in which this grid is divided into five relatively independent cells in the iWoC system. The EMSs of these five cells together with the EMS of the Power Dispatching Center of Hainan Power Grid Corporation constitute an analogous Stackelberg master-slave game framework. The simulation result shows that the effect of frequency control and system operating cost after adopting this approach are obviously better than employing current engineering methods.

However, even for a highly autonomous iWoC, the control mode of the entire system voltage is still adopted an analogous system coordination and cooperation between the AVC of provincial dispatching and prefecture-level dispatching. Moreover, the frequency control of the whole system is also adopted a similar cooperation and cooperation relationship between the AGC system of the provincial-level dispatching and the PLC system of the power plant. In addition, the virtual inertia reserve of the whole system also needs to be assigned to the virtual synchronous generating control system of each cell system in the iWoC. Therefore, we still dynamically allocate the entire goal of the whole system to each cell as a sub-goal through optimization modes, so as to establish an analogous Stackelberg master-slave game framework. Thereby, we can again employ the group reinforcement learning to achieve group intelligent decision-making of the entire iWoC system. Certainly, although we have determined a basic investigation idea for this part, the amount of specific tasks is still huge, which requires in-depth and meticulous work in the future.

B. HYBRID GAMES AND GROUP INTELLIGENT DECISION-MAKINGS AMONG AN INTERCONNECTED SYSTEM AMONG CELLS IN THE WEB WITH EQUAL POSITIONS

In the context of a completely open EM, the principle of justice is more emphasized. Analogously, various COs in the iWoC system pursue to participate in the market competition or cooperation on an equal footing. However, in the complex circumstances, the games between cells are a kind of hybrid gaming process, which are not simple zero-sum games or cooperative games, but general sum games. The issues of hybrid game in the iWoC are very complicated, thus it is essential to focus on solving two dynamic issues as follows.

Dynamic issue 1: it is a dynamic issue that the game relationship will be changed along with the variation of system states under the topology structure of the game among deterministic stakeholders. In particular, at the system-side level, with the change of power grid statuses such as normal, alert, emergence and recovery states, this game process will be experienced with a competitive game, a
partial cooperative game and a fully cooperative game. Hence, the preferences of the Pareto solution set corresponding to the three categories of games will also be changed dynamically, such that we need to employ group intelligent decision-making algorithms, i.e., Nash-Q, Pareto-Q and CE-Q methods to solve the issues of the three types of games, respectively. During the solving process, an intelligent classification for various states can be achieved via using the latest proposed Deep Forest Learning method [120], which can be employed to complete an integration of various ML algorithms.

As demonstrated in Figure 15, a graphical explanation is given regarding the process of dynamic transition between main statuses and control objectives in the process of active power regulation and control in a provincial power grid, where the objective functions of $f_1(X)$, $f_2(X)$ and $f_3(X)$ represent the optimal control performance standard goal, the optimal energy conservation goal and the optimal economic goal, respectively. In this figure, the system status is transferred from an alerting area to a normal zone, and thereby the preference solution is also biased towards the energy-saving and economic goal.

Dynamic issue 2: it is a dynamic issue that the number of agents involved in the game together with the social topology structures will also be changed dynamically in an open and ever-growing EM. To address it, we propose to extend the above-mentioned deterministic game network to a self-organized coupling network, and the relevant investigation on which must be conducted by adopting complex network theory and parallel system theory. For this reason, we have carried out some preliminary explanations, among which we have used the Small World Network model [121-123] in complex network theory together with the parallel system theory [54, 65, 124-126] to investigate the smart generation control of a micro-grid, as illustrated in Figure 16.

In Figure 16, the Small World Network is a kind of special complex network model, which is usually regarded as a type of stable network structure formed during a continuous process of self-organizing in complex networks. It is characterized by information interaction adjacent to each other and tending to the minimum communication cost. We have used intelligent algorithms to implement dynamic random adjustments to the interconnection probability of the group with intelligent decision-making abilities. The results are encouraging and indicate that this variable Small World Network model can successfully avoid the system being trapped into a local optimization. Hence, we believe that a more general self-organized coupling network model can be further used for relevant analysis, and more interesting results will be obtained in the future.

VII. EXPLORATIONS ON SYSTEM DEVELOPMENT AND ENGINEERING PRACTICE OF THE IWOC

In this paper, the theoretical investigation objective is a complete power system consisting of transmission networks and distribution networks. Aiming at engineering practice of this system, we need to put it into practice in some demonstration projects such as the incremental distribution network project and smart distribution network dispatching key science and technology project, such that promoting the application of theoretical results step by step. We believe that some smaller scale of actual power grids may be taken as research targets based on a smart distribution network EMS platform that has been developed previously. For instance, we can consider the Yancheng Power Grid in Jiangsu Province and the Dongguan Power Grid in Guangdong Province as actual investigation objects. Concretely, in the previous stage, we can develop a software platform for the dispatching and control of iWoC in distribution networks, which will be capable of integrating such system platform and the intelligent algorithms which are elaborated in Section III to Section VI. In the later stage, we can attempt to implement engineering practice on the intelligent distribution network dispatching demonstration projects in China.
Southern Power Grid. Specifically, the explorations on system development and engineering practice of the iWoC contain two steps as follows.

- **Step 1:** we need to establish a CPSS-based parallel system platform for the iWoC. This parallel system is suitable for investigating of complex network theory and group game theory. Based on this platform, we can further develop a corresponding software platform for the intelligent dispatching and control system of iWoC;
- **Step 2:** we need to search for some demonstration projects of smart grid, which can be used for engineering practice of the above platforms introduced in Step 1. Then, we should try to carry out some small-scale engineering application practices in order to verify and ameliorate the concept of the iWoC, together with its dispatching and control system and the group intelligent decision-making methods investigated and discussed in this paper.

Specific explanations on the explorations in above two steps are briefly presented as follows.

A. EXPLORATIONS ON THE DEVELOPMENT OF A CPSS PARALLEL SYSTEM-BASED SOFTWARE PLATFORM FOR THE SMART DISPATCHING AND CONTROL SYSTEM OF THE IWOC

In this section, we explore to develop a CPSS parallel system-based software platform for the smart dispatching and control of the iWoC. Such CPSS parallel system for the iWoC is also needed in Section 3 to Section 6 in this paper. Therefore, we deem that the development work of this software platform can be implemented on the self-developed smart grid integrated parallel computing and simulation platform based on multi-agent JADE (i.e., the Java Agent Development Framework), Matlab, and GAMS (i.e., The General Algebraic Modeling System). Among which, JADE is a multi-agent system platform that is developed based on Java language and compliant with the FIPA specification. Hence, we can use JADE to develop this parallel interactive software platform to realize clock synchronization between the physical system and mirrored simulation system during the digital simulation process, as well as parallel interaction of data in a real-time mode. Moreover, we can use the Matlab and GAMS achieve hybrid modeling and programming, so as to implement third-party custom modeling and optimal power flow calculation of a multi-energy flow network. In particular, GAMS can be used as a powerful and advanced modeling system for mathematical programming and optimization to model networks with massive network nodes and solve the optimal power flow of underlying multi-energy flow; while Matlab can be used to implement intelligent learning algorithms programming and complex components modeling via the M-language. Based on the above functional components, we have successfully established a CPSS-based parallel system for the comprehensive energy systems in 2017. This system can be used to train the group smart robots of energy control (i.e., RoboECs) which are proposed previously in [127]. The architecture of this system platform for laboratory investigation is represented graphically as in Figure 17, where we have initially built a CPSS parallel system-based laboratory research platform for such RoboECs in comprehensive energy dispatching, control and management. Therefore, we believe that this laboratory platform for comprehensive energy systems and traditional power systems can be further expanded to a CPSS-based parallel system for the proposed iWoC system in the future.

![Diagram of CPSS Parallel System-Based Software Platform](image)

**FIGURE 17.** Architecture design of the CPSS parallel system-based laboratory research platform for the RoboECs in comprehensive energy dispatching, control and management.

B. EXPLORATIONS ON VALIDATION STUDY BASED ON DEMONSTRATION PROJECTS

In this section, we explore to introduce how to conduct validation research work based on the demonstration projects. Addressed concretely, we can carry out investigation of demonstrated applications in a comprehensive energy demonstration area project which is being constructed by the authors in Songshan Lake Industrial Park, Dongguan City, Guangdong Province. This comprehensive energy demonstration area is presented as graphically in Figure 18. Note that the Songshan Lake comprehensive energy demonstration area in Figure 18 is one of eight key Energy Internet demonstration projects which are being constructed by the China Southern Power Grid.

Figure 18 shows only the first Energy Internet demonstration project implemented by the Dongguan Power Supply Bureau in Songshan Lake Industrial Park. In next step, we will further conduct investigation of demonstrated application for the iWoC in 9 Energy Internet demonstration projects which are implemented by the Huawei Group, China Unicom Data Center, Guizhou Power Grid Corporation, etc. Among them, the aforementioned comprehensive parallel computing simulation platform for the smart grids has been
deployed on a big data analysis platform (i.e., the Hadoop) in 2016, and used to conduct some engineering application researches in an Energy Internet-based comprehensive energy management demonstration project, as shown in Figure 19. This demonstration is selected in a university which is located in Guizhou Province.

FIGURE 18. The architecture design of Energy Internet-based comprehensive energy demonstration in Songshan Lake Industrial Park, where (a) illustrates a complicated integration of the gas network, power network, heating network, and cooling network, which also involves user-side demand management, energy storage and clean-energy generation; and (b) demonstrates a framework design of comprehensive energy management for a cluster of smart buildings, which involves the building energy supply system, power demand side management system, energy storage system, solar thermal collection system, terminal monitoring system, cloud service, and power system.
In summary, we believe that the validation research on the iWoC can be implemented via introducing the CPSS-based parallel architecture to the relevant practical demonstration projects which are being undertaken by the authors, such that relevant theoretical investigation work on the iWoC can be conducted in the future.

VIII. SUMMARY AND PROSPECTS

A. A BRIEF SUMMARY

In this paper, we have investigated the concept, theoretical methods, investigation objectives, and future challenges of iWoC. In general, the theories of self-organized evolution and group intelligent decision-making for the iWoC are the highlights in this paper. Based on these, several key scientific issues to be solved in the future are investigated and discussed in this paper, from perspectives of iWoC system, complex self-organized coupling network, evolutionary game, group ML, parallel system and software system development. A brief summary of this paper is presented as follows:

1) We have investigated the concept of iWoC, which can be seen as an enhancement of the concept of WoC which is put forward by the ELECTRA. The iWoC is a new smart grid architecture whose weakly centralized new dispatching and control architecture can be regarded as a whole systemization of the micro-grid architectures. The ideological essence of iWoC is decentralized autonomy and centralized collaboration.

2) We have proposed, investigated and discussed two key scientific issues of the iWoC to be solved in the future as follows.

The first one is how to establish a self-organized coupling network model based on CPSS integration for the iWoC, which is also a fundamental issue that needs to be addressed in the first place. We deem that this self-organized coupling network model concluded in the complex network theory is a significant model that requires in-depth investigations in the future. From this model, we have a designed a cyber-physical-social system based complex network framework via integrating three categories of networks involved in a power grid, including its physical network, information or cyber network, and multi-stakeholder game network. A double coupling issue including external coupling and internal coupling needs to be solved in each of the three networks, such that the difficulties in modeling and technical challenges will be both high in the future.

The second one is how to achieve the global optimal dispatching and control decision for a certain class of complex systems relying on massive group cells of limited information, weak controllability, small capacity amount and wide distribution in the iWoC, which is a core issue to be tackled in the future in this paper, and also represents the final technical application achievements in the future. To address it, we have conducted systematic investigations via integrating two levels, i.e., the level of independent cell and the system-wide level. During the investigation, complex network theory, group ML and EGT are significant theoretical tools. Moreover, we have combined the relevant investigations to be conducted in the future with the development status of power dispatching systems. Hence, we deem that the related theoretical research achievements must be recognized by the frontline electric power staffs. The investigation on this issue is the biggest scientific innovation in this paper, and it is also the most important key technical barrier that needs to be broken down in the future.

B. PROSPECTS

In the future, we deem that one of the biggest technical challenges is the system development of iWoC. As stated previously, we have established the foundations for the development of an intelligent electricity distribution and utilization software system platform based on Energy Internet technologies, as well as a relatively solid foundation for engineering application. Hence, the conditions for a deep investigation of the iWoC are relatively mature. However, it must be realized that the iWoC investigated in this paper is a brand-new system, instead of a simple and repetitive project development. This investigation requires integrated new theories and new research methods. Therefore, we deem that the difficulties in development of an actual system for the iWoC must be overcome in the future.

We have to acknowledge that the concept of iWoC proposed and investigated in this paper is originated from the concept of WoC which is put forward by the ELECTRA. In addition, the iWoC is also based on an integration of relevant concepts that are proposed by the authors in this paper and other scholars. Although the concept and system of iWoC investigated in this paper are ahead of current status, i.e., the weakly-centralized control system architecture of the iWoC is very different from centralized control architectures applied in current power systems, a challenge we have to face currently and in the future is that the dispatching and operation of power grid more and more rely on high penetration of DGs.

Taking China for an example, the National Development and Reform Commission, the two major Power Grid Corporations (i.e., State Grid Corporation of China and China Southern Power Grid), and the major academic groups in China all no longer have doubts about the above challenge. In China, this challenge is also an important direction for the Smart Grid Joint Fund Project Guidelines. Therefore, we deem that the technical risks that need to be minimized in the future are mainly how to progressively follow up the integrated construction of intelligent dispatching and control of the two major Power Grid Corporations in China, so that...
the theoretical results can be effectively linked with the application of technologies, and the frontline electric power workers can agree with them in practical projects.

Moreover, investigations on complex network theory have been carried out for decades, which have become more and more perfect. Currently, the research highlight of this is mainly focused at the application level. In the future, many scholars [54, 65, 124-127] deem that the parallel system will achieve a significant improvement and a remarkable progress in theoretical and application study of complex systems. Among this, the deep cyber-physical-social integration based CPSS becomes the major and core problem which has been investigated and discussed in this paper. Although a large number of studies have been performed over the CPS, few investigations have involved the consideration of human and social factors. Hence, the introducing of human and social factors to the investigation of the large closed-loop system of the CPSS is the biggest highlight in this paper, which is also the biggest research challenge in the future. To answer it, we believe that the technologies of Internet and Energy Internet will be the key means.

In recent years, many scholars have begun to use the technologies of Internet such as internet of things technology, big data technology, and cloud computing technology to conduct a research on the law of human and social behaviors. Among which, practical achievements have been very rich [64, 128-132]. Hence, based on these investigations, we believe that more and more relevant mature technologies will be adopted combining with artificial society modeling theories developed in recent years to conduct investigations on CPSS in the future. We deem that the risk of this research direction will be controllable and technically feasible.

In addition, EGT and group ML theory are hot topics currently at home and abroad, thus the mature theories and methods of which will build a strong foundation for investigation of iWoC in the future. The related achievements of them are changing with each passing day. Based on these, we have preliminarily established a relatively complete library of ML algorithms, as illustrated in Figure 20. Therefore, we believe that the investigations on the iWoC will be able to conduct at a relatively high starting level.

FIGURE 20. Establishment of a relatively complete library of ML algorithms.

IX. CONCLUSION

The improved WoC, i.e., iWoC, is proposed and systematically investigated in this paper. The iWoC is put forward integrating with the concept of WoC proposed by ELECTRA and the development trend of smart grids in China, which is also reflected in the concept of territory grid and frequency autonomy previously proposed by the authors. The overall framework of iWoC is designed based on the WoC, which can be regarded as an innovative concept of new forms of smart grid containing high penetration of DGs in the future. We will face a challenge that a lot of theoretical and technical research gaps will need to be filled under the framework of WoC put forward by the ELECTRA, and no more detailed technical achievements have appeared so far. In this context, this paper systematically and profoundly expounds the relevant theoretical investigation contents and key scientific issues to be solved in the future from the perspectives of modeling method, stability analysis and design of control strategy for decision-making of power system dispatching. In general, the main contributions of this paper are summarized as follows:

1) Based on a variety of advanced theoretical tools such as complex network theory, group ML and EGT, the following four basic scientific issues for future development of iWoC are thoroughly investigated: four basic scientific issues: the modeling method of self-organized coupled network of the CPSS-based iWoC; the stability analysis and stability control system of the self-organized evolution of iWoC; a highly autonomous group intelligent decision-making method of an independent cell in the iWoC; multi-cells synergetic
evolutionary game and group intelligent decision theory. Thus, an innovative breakthrough on intersection of complex network game theory and group ML is obtained, contributing to the emergence of group knowledge in complex system environment and a significant improvement in the level of group intelligent decision.

2) We first propose to investigate the iWoC via integrating the theory of complex self-organized coupling networks with the modeling theory of CPSS integration. We propose to include three categories of networks for investigation of the iWoC, i.e., the electricity network (or physical network), the information network (or cyber network), and the market trading and gaming network (or social network). Due to the topological self-organizing characteristic of iWoC, we propose to use the complex network theory to investigate each of them. We deem that such self-organized coupling network is a kind of self-organizing model in complex networks, thus this special network is very suitable for studying the three networks.

3) Moreover, we first propose to integrate the three networks so as to form the CPSS-integrated iWoC model, which is highly innovative. In this paper, we deem that the theory of complex self-organized coupling networks and theory of CPSS integrated modeling should be combined, such that its basic theory and industrial application are both highly innovative in the fields of industry and power system.

4) Lastly, we first propose to investigate the iWoC via combining the complex self-organized coupling network theory with the theory of group intelligent decision-making in the field of smart grid. Here, the complex self-organized coupling network theory belongs to complex network theory, and is the theory for investigating the topology change of networks and the networks' own dynamic performance. The ML-based group intelligent decision-making theory belongs to the control engineering field, which is used for investigating the dynamic process of the entire system composed of agents and controlled objectives. However, we believe that these two kinds of dynamic processes are fundamentally different, and they have been investigated separately as two completely decoupled issues in the field of power system. In this paper, we have investigated the iWoC via integrating the dynamics regularity of network topology with the dynamics behavior of intelligent system due to disturbances, based on its self-organizing characteristics. It was the first time to conduct this integrated investigation form in the field of smart grid. Therefore, this investigation on the iWoC not only has the considerable difficulty and challenge, but also plays a significant role in promoting the emergence of group knowledge and group intelligence for complex systems such as smart grids.

The biggest innovation of this paper lies in thoroughly investigating how to implement the overall optimal scheduling and control decision-making of a class of complex systems relying on massive group cells with characteristics of limited information, weak controllability, small capacity, and wide distribution.

**APPENDIX**

\( x_i(t) \) \hspace{1em} state vector of the node \( i \)
\( i, j \) \hspace{1em} the \( i \)th or \( j \)th node in a network
\( f(x_i(t)) \) \hspace{1em} continuous vector-valued function
\( \Gamma \) \hspace{1em} inner-coupling matrix
\( c \) \hspace{1em} strength of coupling
\( A_{EC} \) \hspace{1em} external-coupling matrix of network topology structure
\( a_{ij} \) \hspace{1em} the element on row \( i \) and column \( j \) of the matrix \( A_{EC} \)
\( r_{ij}(t) \) \hspace{1em} transition probability of Markov chain
\( \pi(t) \) \hspace{1em} time-varying delay
\( N \) \hspace{1em} total number of nodes in a network
\( A, B, C, D \) \hspace{1em} Jacobian matrices of the non-linear function matrix after linearization
\( f(k), g(k) \) \hspace{1em} non-linear function vectors in the \( k \)th iteration
\( \tau_1, \tau_2 \) \hspace{1em} time delays
\( u(k) \) \hspace{1em} control input matrix in the \( k \)th iteration
\( k \) \hspace{1em} the \( k \)th iteration
\( l \) \hspace{1em} the \( l \)th decision agent
\( \pi_l \) \hspace{1em} probability distribution of state-action of the \( l \)th decision agent
\( Q^l_k \) \hspace{1em} knowledge matrix of the \( l \)th decision agent at the \( k \)th iteration
\( s_k \) \hspace{1em} state of the multi-agent system at the \( k \)th iteration
\( \tilde{a} \) \hspace{1em} joint action of all the decision agents
\( a_l(t) \) \hspace{1em} action of the \( l \)th decision agent
\( L \) \hspace{1em} number of the agents
\( \hat{a}_l \) \hspace{1em} joint action of all the decision agents except the \( l \)th decision agent
\( A(s_k) \) \hspace{1em} the agents’ set of available joint actions in state \( s_k \)
\( A_l \) \hspace{1em} the \( l \)th decision agent’s set of pure actions
\( a^l \) \hspace{1em} the \( l \)th decision agent’s any other action except the action
\( a_l \)
\( V(s_{k+1}) \) \hspace{1em} state value-function of the \( l \)th decision agent in state \( s_{k+1} \)
\( \alpha \) \hspace{1em} knowledge learning factor
\( \gamma \) \hspace{1em} discount factor
\( R_l(s_k, \hat{a}_l) \) \hspace{1em} feedback reward after implementing a joint decision-making action \( \hat{a}_l \) under state \( s_k \)
\( m \) \hspace{1em} the \( m \)th follower in a Stackelberg game
\( M \) \hspace{1em} the total number of the followers in a Stackelberg game
\( \bar{X_l} \) \hspace{1em} current optimal strategy of the leader
\( \bar{X}^l \) \hspace{1em} the joint optimal strategy of all followers
\( \bar{X}^l \) \hspace{1em} current optimal strategy of the \( l \)th follower
\( U_{leader} - U_l \) \hspace{1em} the payoff functions of the leader and the \( l \)th follower, respectively
\( A_{leader} - A_l \) \hspace{1em} the decision-searching space of the leader and the \( l \)th follower, respectively
\( M \) \hspace{1em} the total number of followers who interact with the follower \( m \)
$Q_a$ the total number of real code for transfer learning
$P_S$ the total number of searching for the follower $m$
$R_C^{m}\theta$ an immediate feedback reward, which can generally be transformed from the optimal objective
$Q_{mt}^{\alpha\beta}$ the knowledge matrix and its increment, respectively
$\Delta Q_{mt}^{\alpha\beta}$ a random value in the unified probability distribution
$\Delta$ a parameter of local greedy searching
$\alpha_{rand}$ the global random searching action
$\text{CPS}_1$ the index system of control performance standard
$\text{CPS}_2$ the optimal control performance standard goal, the optimal energy conservation goal and the optimal economic goal, respectively
WoC web-of-cells
iWoC improved web-of-cells
ML machine learning
CPSS cyber-physical-social systems
IEA International Energy Agency
DG distributed generation
EM electricity market
EMS energy management system
NSFC National Natural Science Foundation of China
ELECTR A IRP long-term Research Activity Integrated Research Programme
CO cell operator
TSO transmission operator
DSO distribution operator
MDP Markov decision process
AI artificial intelligence
ANN artificial neural network
GAN generative adversarial network
BPNN back propagation neural network
SVM support vector machine
ADP adaptive dynamic programming
EGT evolutionary game theory
MSCDG Markov switching complex dynamic grid
PGE power grid enterprise
EV electric vehicle
NPSE new power supply entity
EC electricity consumer
AEG asymmetric evolutionary game
GenCo generating corporation
CPSS cyber-physical systems
MESS multi-group evolutionary stable strategy
RD replicator dynamics
ASEP asymptotically stable equilibrium point
ESS evolutionary stable strategy
VAPS virtual artificial parallel system
ACP artificial society, computational experiments, and parallel execution
PVC primary voltage control
PPVC pose-primary voltage control
IFC inertia frequency control

REFERENCES

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