Parallel Dispatch: A New Paradigm of Electrical Power System Dispatch

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***Abstract*—Modern power systems are evolving into socio-technical systems with massive complexity, whose real-time operation and dispatch go beyond human capability. Thus, the need for developing and applying new intelligent power system dispatch tools are of great practical significance. In this paper, we introduce the overall business model of power system dispatch, the top level design approach of an intelligent dispatch system, and the parallel intelligent technology with its dispatch applications. We expect that a new dispatch paradigm, namely the parallel dispatch, can be established by incorporating various intelligent technologies, especially the parallel intelligent technology, to enable secure operation of complex power grids, extend system operators' capabilities, suggest optimal dispatch strategies, and to provide decision-making recommendations according to power system operational goals.**

***Index Terms*—ACP, knowledge automation, power dispatch, parallel dynamic programming, parallel intelligence, parallel learning, situational awareness.**

I. Introduction

ELECTRICAL power grids are in the transition from traditional power grids to modern smart grids to accommodate rapid development of human society. It has been predicted that electricity demand in 2030 will be the double of the demand in 2010 [1]. Expansion of power generation and renovation of transmission and distribution infrastructures, which cause tremendous consumption of public resources, cannot be the only solution to this social requirement. All stakeholders in the power industry, including the society, government, electricity providers, consumers, and power transmission and distribution operators, are desperate for a much more efficient operating system, so that the burden and pressure brought by the rapid demand growth can be mitigated. Meanwhile, regulation and customer demand on higher service quality and system reliability also become important considerations of the stakeholders. Global initiation of environment protection and carbon dioxide emission reduction substantially constrain the development of conventional power systems based on fossil energy, while promote the utilization of renewable energy sources. The features of renewables, e.g., intermittence, uncertainty, and difficulty of being integrated into grid operation, are the foremost problems to be solved by researchers and engineers. The rise of modern smart grids brings in huge impacts on dispatching systems, which are summarized as following.

Under the above mentioned circumstances, development of the modern smart grids reveals the following new requirements for dispatching systems.

1) The electricity consumers are expecting less supply shortages. The consumers are expecting more reliable power supply, lower possibility of outages, cheaper electricity prices, and better living environment [2].

2) Professional expertises and amount of the electricity dispatching personnel should be improved. Since the dispatchers in the power system are managing systems with increasing scale, complexity and infrastructures, they are required to improve their capabilities for higher professional knowledge and skills. And the temporal and monetary investments for training an advanced electricity dispatcher are huge, which may further lead to a larger gap in the amount and quality of such personnel.

3) The dispatching system should be adaptive to the frequently updated power system infrastructures. Infrastructures of the power systems have to be updated frequently to catch up with the pace of society development. And the newly updated infrastructures will bring both predictable and unpredictable effects to the electricity dispatching [3].

4) Environment protection and emission reduction should take high priority. Connection of large scale renewable energy generations, utilization of UHVDC system, and coupling and combination of traditional and new energy sources, all these techniques and events will challenge the way electricity being transmitted today [4].

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5) Evolutions of electric power technologies would bring challenges. The rise of distributed electricity generation, smart scale renewable energy application, energy storage devices, microgrids, and electric transportation will add new and uncertain influences to grid operation, which will introduce new, uncertain and huge challenges to the electricity dispatching system [5]−[8].

The emerging technological trend of smart grid also brings major changes and challenges in system operators' responsibility and requirements, which are explained as the following.

6) A large amount of sensors and actuators emerging in the modern smart grids substantially increase the difficulty and complexity of electricity dispatching, which goes beyond the limitation of human capability. This forces the dispatch system to transform from a centralized and manually operated one to a supervised AI-based, centralized+distributed, and highly effective dispatching system. Therefore, the development and applications of new dispatching tools are of great practical significance.

7) In electricity transmission systems, emerging remote sensing devices, such as synchrophasor measurement units, can provide the operators more detailed real-time information about the system. However, the amount of data is too large for the operator to interpret manually. Furthermore, in order to fully unveil and utilize the information embedded in the data, such as system state and situation awareness, advanced data analysis tools and intelligent algorithms are required.

8) In electricity distribution systems, the distribution-level dispatch will begin to utilize modern control and monitoring systems, such as distribution management system (DMS), outage management system (OMS), supervisory control and data acquisition (SCADA) and geographic information system (GIS). These systems will work interactively to achieve autonomous operation of the distribution system, in which artificial intelligence will play an important role.

9) For electricity generation, operators are altering the traditional dispatch paradigm, which directly controls only a small amount of generators, to a new paradigm, which combines both centralized and distributed generators (DGs). The generation capacity of a distributed generator is usually small, but the number of DGs can be very large, with some of them being controllable and some being not. Therefore, for DG cooperation, the dispatch systems should possess the ability to work at least semi-automatically and semi-autonomously.

10) The emergence of new electrical technologies, such as ultra high-voltage direct current (UHVDC) transmission, large-scale renewable energy, advanced metering infrastructure (AMI), demand side management, and demand response, has enabled new grid operation patterns, e.g., virtual power plants, large-scale renewable energy accommodation, etc. How to dispatch electricity with such new operational patterns remains an issue to be discovered. Regarding such new patterns with very little operational experience from industry, artificial intelligence can conduct effective numerical situational analysis, which could provide reliable basis for system decision making.

11) The security and privacy of Smart Grids create strong impacts on system dispatch due to extensive applications and vulnerability of sensing and communication systems. For example, if an operator makes a dispatch strategy according to maliciously manipulated data, the consequences could be catastrophic and irreversible. Thus system security also becomes a vital component of power system dispatch.

All the aforementioned technological trends will lead to substantial alterations in work patterns and duties of grid operators. System operators should be able to react to more complicated systems in real time. Artificial intelligence could be the extension of system operators' capabilities, providing optimal dispatch strategies through learning, computing, reasoning and decision-making recommendation according to system operation goals.

II. Decision-making and Knowledge Automation: Top Level Design

As shown in Fig. 1, electricity generation, transmission & distribution and customer are the core business elements in power grid operation [1], [9], [10]. To serve for these core business elements, some peripheral services also need to be provided, including company operation, investment management, regulation supervision, etc.

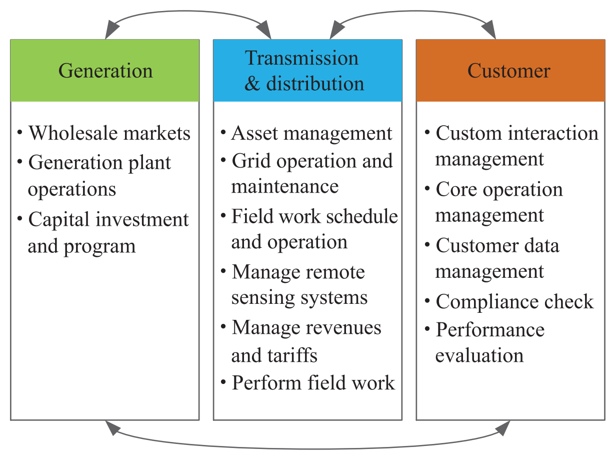

Fig. 1. The general business model of power grids operation.

In an intelligent power dispatch system, an intelligent technology framework is essential for organizing these services to form a whole integrated system, and the final goal is to achieve decision-making and knowledge automation for these services. The top level design of the intelligent dispatch system aims at solving the following problems: 1) How to integrate all the dispatching services into one united intelligent system while keeping each of them working independently. 2) How to encapsulate related data sources and intelligent techniques into each service, and extract required knowledge and information.

Decision-making and knowledge automation (DKA) is a scientific management approach. It connects all the related services together in an operating system, conducts evaluation, boundary definition, data source definition and knowledge encapsulation for each service [11]. DKA defines the interactive mechanism among different dispatch services, and the data and intelligent approaches for each particular dispatch service, therefore, realizes automation in decision-making and knowledge generation. The details of DKA include:

1) Value estimation: How to define a measurable value for the service related knowledge.

2) Process modeling: How to model the entire decision-making process utilizing only a group of the decision points in this process, and how to automate the decision-making process using decision services, which have been encapsulated with necessary service knowledge. These services will be published by business rule management systems (BRMS), and be called by business process management systems (BPMS).

3) Knowledge encapsulation: Encapsulation of business rules, algorithms and predictive analysis tools, framework establishment for automatic decision-making; determining the four critical components supporting the decision-making, i.e., BPMS, BRMS, predictive analysis models, and database.

4) Decision requirement analysis (DRA): Decomposition of the decision-making process into network structures, which can be described by decision requirement diagrams (DRD). DRD illustrates the relationships among decision-making, knowledge domain and data domain.

5) Development of knowledge automation projects: Demonstration of all the critical points in organizing a knowledge automation project utilizing DRD structure, which are scope classification, service estimation, project planning, knowledge discovery, design, development, configuration and testing. To modularize the decision-making process using DRA can create highly efficient knowledge production lines.

6) Intelligent techniques for discrete and hybrid system modeling, such as Petri net and its variations, are common approaches to design service structures.

III. Dispatch Control Center Models

A. Control Center Hardware System Model

The hardware system model of a dispatch control center (DCC) consists of three information networks as following.

1) Front-end networks: Interacting with the front-end data collection systems which consists of a number of terminal servers; communicating and exchanging information with remote RTUs; providing information for and taking orders from analysis network.

2) Analysis network: Reading power grid data and information from front-end networks; achieving analysis and decision-making for SCADA, energy management system (EMS), DMS, OMS, etc.; consisting of a number of work stations to provide services for different grid operations.

3) DTS networks: Training operators; interacting with analysis network; using data and models from the Analysis Networks; used as simulation systems in network analysis.

4) Other system components: Including visualization system interface, enterprise management information system (MIS) networks, display boards, database servers, etc.

To accommodate AI technology, the dispatch control center needs the following additional support hardware facilities.

5) Adding an intelligent network: Intelligent network equipment includes large-scale data server, high-performance parallel computing facilities, and human-machine interaction mechanisms such as data visualization servers, etc. The intelligent networks reads real-time data from front-end networks and historical data from database, for training, updating and deploying intelligent algorithmic software.

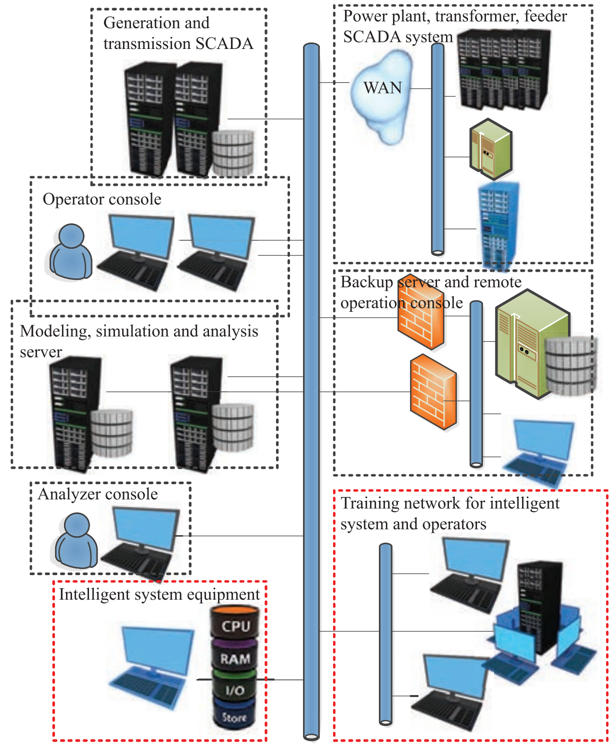

Fig. 2. The hardware system model of a dispatch control center (DCC) supporting intelligent technology.

6) Updating DTS networks: After intelligent tools are deployed, the responsibility of DTS networks also includes providing simulation support to intelligent algorithm training. As a result, the DTS network needs to be equipped with substantially increased computational capabilities. In the mean time, as the operators are going to utilize AI tools for system dispatching, the contents of their training needs to be updated substantially.

B. Control Center Software System Model

The model of control center software is described as following (Fig. 3).

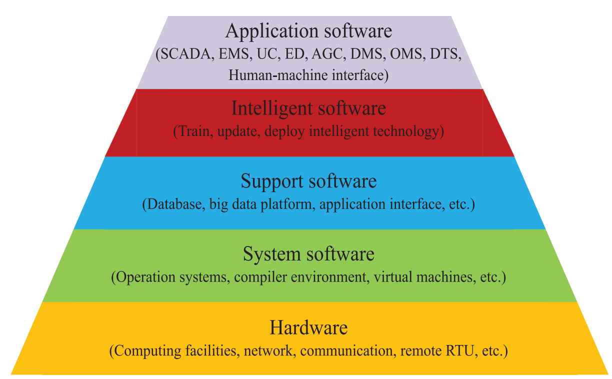

Fig. 3. The software system model of a dispatch control center (DCC) supporting intelligent technology.

1) Transmission Control Center:

a) Transmission Control Console: Transmission control console software takes charge of the overall safety of the power grid. Transmission control monitors the power grid by collecting and analyzing system data in real-time, including SCADA signal analysis, state estimation, power flow analysis, contingency analysis, optimal power flow analysis, system security analysis, etc.

b) Generation Control Console: Generation control console conducts non real-time operations, such as day-ahead generation planning, hours-ahead generation planning. Generation control ensures the balance between power generation and consumption throughout the grid, with minimal economic and social costs. Its application software includes unit commitment (UC), economic dispatch (ED), automatic generation control (AGC), etc. In the process of conducting UC, ED and AGC, generation control will frequently interact with electricity markets, as a result, generation control also participates, or even dominates, electricity market activities.

c) Work Schedule Control Console: Work schedule control console plans and schedules future power grid activities, such as consumer access requests, generator access requests, outage requests, etc.

2) Distribution Control Center: The operation of distribution control center is different from transmission control center [12]. The development of smart grid directly and dramatically affects the power distribution system. The responsibility of power distribution system software includes providing safety management and breaker on/off management for distribution system field work; providing effective system asset management and field work resource management; and coordinating related work force departments and personnel on conducting effective field work, such as maintenance, emergency operation, equipment replacement, etc. Currently, DMS and OMS provide and conduct the above operation.

3) Operator Training Simulation Software and Other Critical Software: Dispatcher training simulation software system is used to train operators to conduct swift and correct dispatch action under normal and abnormal grid conditions, also it is used for simulating and analyzing power grids. Other critical software systems include display board software, alert system software, dispatch action tracking and censoring, backup dispatch system, cyber-physical security systems, etc.

4) Incorporating Artificial Intelligent Software: The artificial intelligent software is positioned as support software for power grid dispatch applications, which trains, updates, implements and deploys AI techniques and algorithms. As a result, application software (SCADA, EMS, UC, ED, AGC, DMS, OMS, DTS, etc.) should provide interface with artificial intelligent software to utilize the AI support in detection, estimation, reasoning and decision-recommendation.

IV. Parallel Dispatch: A New Paradigm

Intelligent technologies covers many research areas, including optimization, searching, agent-based systems, programming, reasoning, knowledge representation, decision making, machine learning, natural language processing, robotics, etc. After various dispatch services are encapsulated in the decision-making and knowledge automation system, each service is to be implemented by different intelligent technology according to its inherent characteristics and goals. In this section, we address a cutting-edge intelligent technology, the parallel intelligent technology, and its applications in power system dispatch [13]. It is expected that a new dispatch paradigm, namely the parallel dispatch, can be established by incorporating parallel system theory, parallel situation awareness techniques, parallel learning techniques and parallel dynamic programming techniques into the field of power system dispatch.

A. Parallel System Theory and ACP Approach

The characteristics of parallel system theory include data-driven modeling, artificial systems, and analytics based on computational experiments. The core concept of the parallel system theory is to establish one or multiple virtual artificial systems in the cyber space in corresponding with the real physical system under investigation. The virtual systems are with various purposes such as scheduling, testing, control, management, etc. Through investigating and shaping the virtual systems, and interacting with the real physical system, the goal of management and control of the real physical system is achieved [14]. It is worthy of noting that, recently, parallel learning [15] and parallel dynamical programming [16] are derived from the parallel system theory.

The creation of the virtual artificial systems utilizes a complex system analytic approach, i.e., the ACP approach [17]. The ACP approach consists of "artificial systems" (A), "computational experiments" (C) and "parallel execution" (P) [13]. In the context of power grid dispatching, the ACP approach is described as following.

1) Artificial Systems (A): Utilizing data from the real physical world and the virtual artificial world, through mining the data, discovering the embedded "intrinsic meaning", meanwhile together with data-driving and semantic modeling, one can construct artificial systems to pair with the real physical system by Merton's law;

2) Computational Experiments (C): It is difficult to use a single analytic mathematical model to describe all the possible power grid dynamic conditions, instead, the dynamics needs to be modelled by computational experiments. Computational experiments utilizing "social computing approaches" integrate important social and environmental factors in power grid operation such as consumers, social activities, weather, policy & regulations, etc. In such way, a deeply integrated socio-technical system model is created.

3) Parallel Execution (P): The virtual artificial power system and real power system are paired to form a parallel system, the interactions of the virtual and real systems generate the feedback mechanism for controlling and managing the physical processes in the real system.

B. Parallel Learning and Deep Networks

Deep learning (DL) is a branch of machine learning [18]. Currently, the major frameworks of DL include deep neural

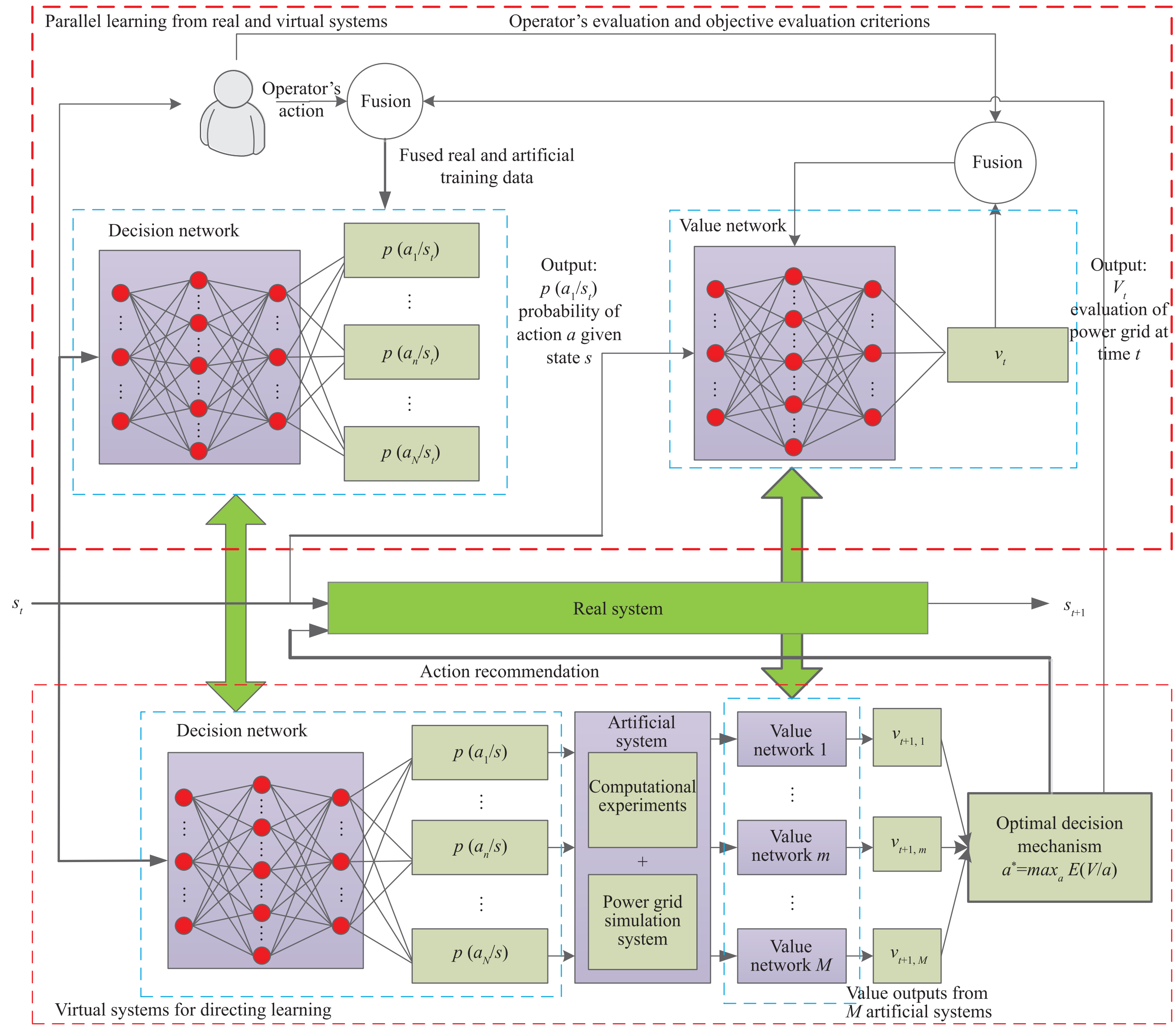

Fig. 4. The parallel learning for power system dispatch.

networks, convolutional neural networks, deep belief networks, recurrent neural networks, etc. The DL approaches are being applied in many research fields such as computer vision, audio recognition, natural language processing, biological informatics, and achieved tremendous success. Utilizing the synergy of DL and parallel system theory, a new framework of machine learning theory, parallel learning, is proposed in [15], which incorporates and inherits many elements from various existing machine learning theories. Special designs can be incorporated into the parallel learning framework to address important issues in the machine learning research field, e.g., effective data retrieval from big data using software defined artificial systems, combination of predictive learning and ensemble learning, application of Merton's law to prescriptive learning, etc.

Application note in electric power system dispatch: An important mission of intelligent power system dispatch is to convert system operators' experience, including historical operation actions in successful and failed dispatch, historical dispatch records, and related historical dispatch data, into intelligent technical models. Utilizing the parallel learning framework, an example of PL for power system dispatch is depicted as following. Two deep networks are going to be learned from the dispatch system, the "decision network" (DN) and the "value network" (VN). The inputs of DN are system's states and related observation s_k, such as map board display, system state observations, and system equipment states. The outputs of DN are operators' decision on actions, more exactly, are $p(a|s_t)$ the probability of action a given system state s_t. The inputs of VN is system's states and related observation s_k, and the outputs v_t are the overall evaluation on different power grid performance criterions. Integrating the DL networks (VN and DN) and the parallel power system, the parallel learning for power system dispatch is demonstrated in Fig. 4. In this learning system, utilizing historical power system dispatch records, the VN and DN are initially trained. In the virtual system, given the real-world power system states s_t at time t, various operational conditions are simulated by computational experiments and power system simulation. Corresponding to M computational experiments, a state ensemble $\hat{s}_{t+1,m}$, $m = 1, \ldots, M$ and their evaluation $v_{t+1,m}$ are generated in the virtual systems. Utilizing the outputs from the artificial systems, the optimal action a_t^* is determined using an optimal decision mechanism. The a_t^* derived from the virtual system is fed into the DN learning process to adjust the DN model for better action modeling through reinforcement learning. For training the VN, the operator's evaluation and the VN's output are compared to adjust the VN model.

C. Parallel Situational Awareness

Situational awareness, in the context of power grid operation, aims to solve power grid security operation problems. Situational awareness implements power grid critical dynamic data's real-time measurement and analysis to achieve system behavior's measurements, identification, visualization and early warning. Technically, situational awareness incorporates wide-area monitoring on network dynamics, mining of multimodal sensor data, dynamic system parameter identification, faster-than-real-time simulation, data visualization techniques, etc.

Combining parallel system technology, we propose a new technical framework of situational awareness, namely, parallel situational awareness. Specifically, parallel situational awareness (PSA) utilizes large-scale graph processing techniques to describe system states and model power grid dynamics. Utilizing historical operation data and their graphic description, the power grid states are clustered by using large-scale clustering algorithms. The state clusters formed from the clustering algorithm serve for the classification and evaluation of power grid states, such as normal, abnormal, stable, unstable, faulty state classes, etc. Through labeling (or semi-supervised labeling) the state clusters, system anomaly detection become feasible, i.e., if the current state does not belong to any state clusters that are labelled as "normal" state clusters, system anomaly is detected. Similarly, if the current system state falls into a certain "faulty" state cluster, a system fault is detected and identified.

In Fig. 6, one sample scheme of parallel situational awareness is demonstrated. Modern power grid operation is very stable, which means anomaly and faulty states appears with very small probabilities. As a result, the data volume generated under these conditions is very small, and cannot satisfy the needs for AI algorithms such as deep learning. To tackle this challenge, the following critical techniques are proposed as the major solutions: 1) parallel artificial systems: through modeling and studying parallel systems, generating data under most possible and critical operation conditions, to conduct computational experiments of the complex power system; 2) deep learning: transferring historical operation data and operators' actions into Big Data model; 3) reinforcement learning: incorporating real-time dispatch and operation data into the situational awareness system. Specifically, the following list includes an exemplar technical work procedure of parallel situational awareness.

1) Generating artificial system parameters and scenarios from historical grid operation data under stochastic loading, generation, fault, and anomaly conditions.

2) According to the generated parameters and scenarios, constructing multiple artificial system, together with computational experiments and simulation systems, generating data from artificial systems.

3) Utilizing the clustering models trained from both historical data and artificial data, the current state is evaluated.

4) Training power grid state transfer models, and conducting reinforcement learning on these models using historical and real-time data.

5) Training real-time situation evaluation network, and conducting reinforcement learning on these models.

6) Utilizing power grid state transfer models, real-time situation evaluation network, artificial systems, to achieve situational awareness and evaluation results.

D. Parallel Dynamic Programming

Integrating adaptive dynamic programming theory and parallel system theory, a new framework of dynamic programming, the parallel dynamic programming (PDP), is proposed in [16], [19]. PDP is able to incorporate various modern intelligent techniques into its framework, such as aforementioned parallel learning, deep learning, deep network, reinforcement learning, rule-based expert system, etc. The PDP greatly enhances the capability and applicability of dynamic programming to complex social systems and engineering systems, by introducing the ACP approach. One example of its application in power system dispatch is depicted as following.

Application note in electric power system dispatch: In the PDP system for power system dispatch (Fig. 5), the two deep networks "decision network" (DN) and "value network" (VN) are utilized which play important roles. The DN and VN are learned from the parallel dispatch system as introduced in Section IV-B. Also, a critic network (CN), for approximating dynamic programming performance index, is going to be learning in the PDP process. The work flow of the PDP system is described as following.

1) Assuming the system state is s_t at time t, the DN generates the probability $p(a|s_t)$ which is the probability of action a given state s_t.

2) According to $p(a|s_t)$, the software-defined artificial system is utilized which is the combination of computational experiments, power system simulation, and value network (VN). The possible outputs of the artificial systems are $\hat{s}_{t+1,m}$, and its evaluation $v_{t+1,m}$, with $m = 1, \ldots, M$ being the index of the mth computational experiment. The computational experiments include variations in social activities, weather fluctuations, renewable energy intermittence, system anomaly, etc. And we name this system as a "1-to-M system".

3) Each output of the "1-to-M system", i.e., $(\hat{s}_{t+1,m}, v_{t+1,m})$, is fed into another "1-to-M system" to generate possible system states and evaluations for time $t+2$. The outputs of all the 1-to-M systems go through a "reduction mechanism" to eliminate branches with low probabilities and/or low values.

4) Repeating the above process in the virtual system until $t + L$ (in virtual system time).

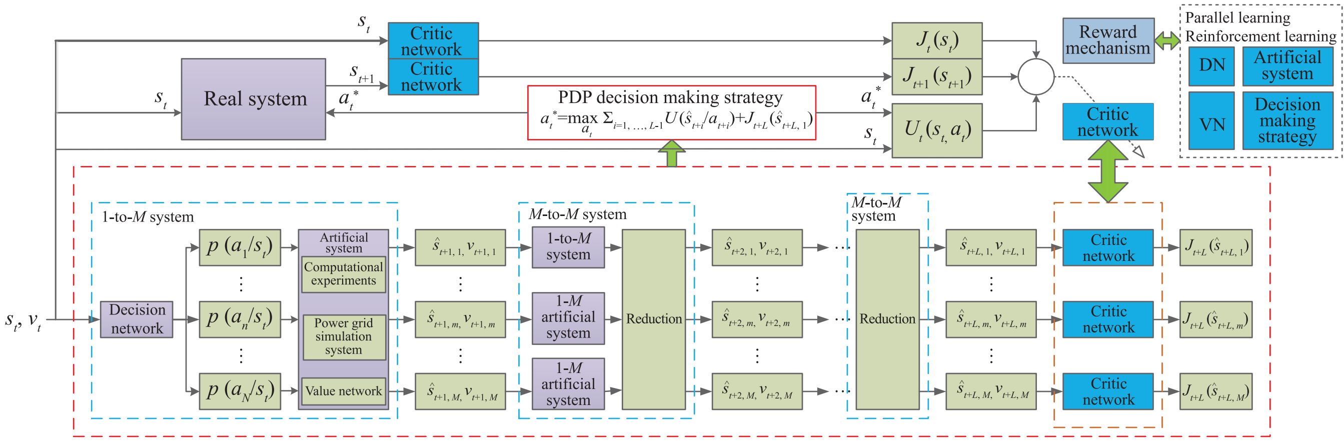

Fig. 5. Parallel dynamic programming for power system dispatch.

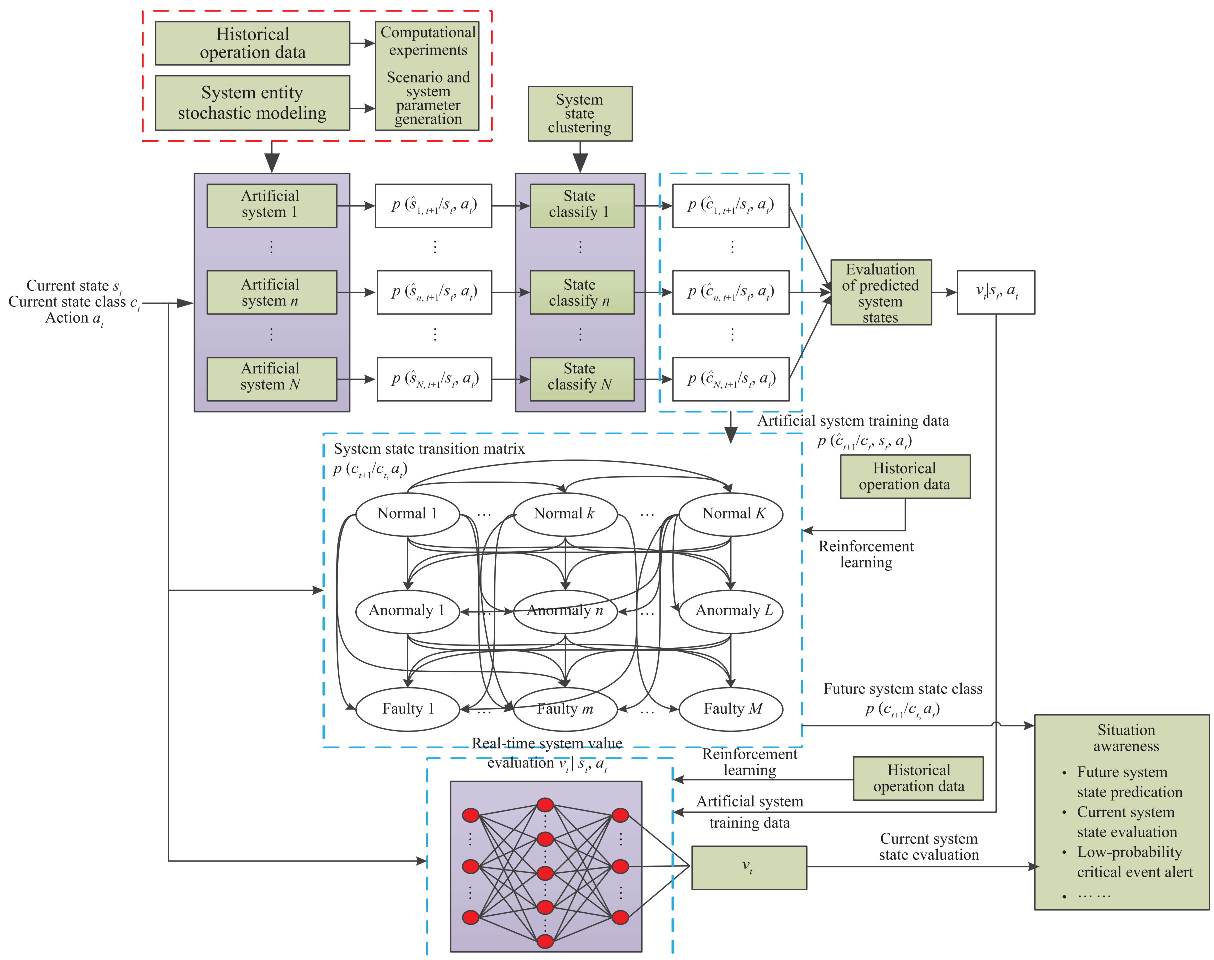

Fig. 6. Parallel situational awareness for power system dispatch.

5) Using a critic network (CN) to generate the estimate of dynamic programming performance index $\hat{J}_{t+L}(\hat{s}_{t+L,m})$, $m = 1, \ldots, M$.

6) Determining PDP decision by $a_t^* = \max\limits_{a_t} \sum_{i=0}^{L-1} U(\hat{s}_{t+i}, a_{t+i}) + \hat{J}_{t+L}(\hat{s}_{t+L,m})$. $U(s_{t+i}, a_i)$ is the single-step merit brought by the combination of $(\hat{s}_{t+i}, a_i)$'s probability and $v_{t+1,m}$, noting that Monte Carlo tree search (MCTS) and back propagation are two examples of such decision-making algorithm.

7) After the optimal decision a_t^* is determined, it is applied to the real system, and the system state transfers to s_{t+1}. According to s_{t+1}, $\hat{J}_t(s_t)$, $\hat{J}_{t+1}(s_{t+1})$ are calculated by CN, and $U(s_t, a_t)$ in the real system is calculated accordingly. The

difference of $e_t = U(s_t, a_t) + (\hat{J}_{t+1}(s_{t+1}) - \hat{J}_t(s_t))$ is used to train CN to force e_t to be zero.

8) According to a "reward-penalty" mechanism, reinforcement on learning of DN, VN and CN is applied to further enhance the accuracy of the learned deep networks.

V. Conclusions and Our Vision

Modern smart grids are evolving into socio-technical systems with massive complexity, whose real-time operation and dispatch go beyond human capability. Thus, the development and applications of new intelligent power system dispatch tools are of great practical significance [3], [20]. In this paper, we introduce the overall business model of power system dispatch, the top level design approach of an intelligent dispatch system, and the parallel intelligent technology with its dispatch applications. We expect that a new dispatch paradigm, namely the parallel dispatch, can be established by incorporating various intelligent technologies, especially the parallel intelligent technology, to enable secure operation of complex power grids, extend system operators' capabilities, suggest optimal dispatch strategies, and to provide decision-making recommendations according to power system operational goals.

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