Cyber-Physical Electrical Energy Systems: Challenges and Issues

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***Abstract*—Cyber-physical electrical energy systems (CPEES) combine computation, communication and control technologies with physical power system, and realize the efficient fusion of power, information and control. This paper summarizes and analyzes related critical scientific problems and technologies, which are needed to be addressed with the development of CPEES. Firstly, since the co-simulation is an effective method to investigate infrastructure interdependencies, the co-simulation platform establishment of CPEES and its evaluation is overviewed. Then, a critical problem of CPEES is the interaction between energy and information flow, especially the influence of failures happening in information communication technology (ICT) on power system. In order to figure it out, the interaction is analyzed and the current analysis methods are summarized. For the solution of power system control and protection in information network environment, this paper outlines different control principles and illustrates the concept of distributed coordination control. Moreover, mass data processing and cluster analysis, architecture of communication network, information transmission technology and security of CPEES are summarized and analyzed. By solving the above problems and technologies, the development of CPEES will be significantly promoted.**

***Index Terms*—Cyber-physical electrical energy systems, information communication technology, power system, smart grid.**

I. Introduction

AT present, more and more attentions are paid to the development of smart grid, in purpose of sufficient utilization of sustainable energies and to improve the safety, reliability and efficiency of power grid. Information technology plays a crucial role in smart grids [1], [2]. System state estimation, control, optimization and self-healing are main functions of smart grid, which are impossible to be implemented without the high-speed & bi-directional communication infrastructure, advanced information processing and distributed computation technologies. Emerging issues, like information safety, mass data processing, communication reliability, and so on, generate profound influence on grid operation. The traditional power grid modeling, analysis and control methods cannot take the influence of information system into consideration and only consider them independently.

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Cyber-physical electrical energy systems (CPEES) integrate power and information networks, which consists of plenty of sensors, communication network, and physical, computation and control systems. The communication network connects sensors, computation and control units together to realize information sharing in the whole system. Meanwhile, based on shared information and distributed computation technology, the identification, optimization and control of physical system can be performed. By the fusion of power, information and control, physical entities can be provided with functions of computation, communication, accurate control, coordination and autonomy [3], to improve the safety, reliability and efficiency of power system. Besides, CPEES can also coordinate with other social systems, like transportation system, and with environment.

With the development of smart grid, physical electrical equipments and data collection and computation equipments are closely interconnected by communication network and smart grid becomes energy and information coupled infrastructure, which makes smart grid become CPEES. By the fusion and interaction of physical and information processes, CPEES monitor and control power system in a secure, reliable and efficient way and realize the coordination of power system, environment and other social systems. However, CPEES, as shown in Fig. 1, are an integrated system and its development faces problems of co-simulation platform establishment and evaluation, interaction between power and information flow, power system control and protection and so on. The contribution of this paper is the summary and analysis of critical scientific problems and technologies in CPEES. In the following, the review of co-simulation platform establishment of CPEES and its evaluation are presented in Section II. In Section III, the interaction between the energy and the information flow and corresponding analysis methods are presented. Next, Section IV discusses power system control and protection in the information network environment. Mass data processing and cluster analysis of grid operation state, architecture of communication network, information transmission technology and security of CPEES are presented in Section V. Finally, a conclusion is given in Section VI.

II. Co-Simulation and Evaluation of CPEES

Simulation is a common method to evaluate the performance

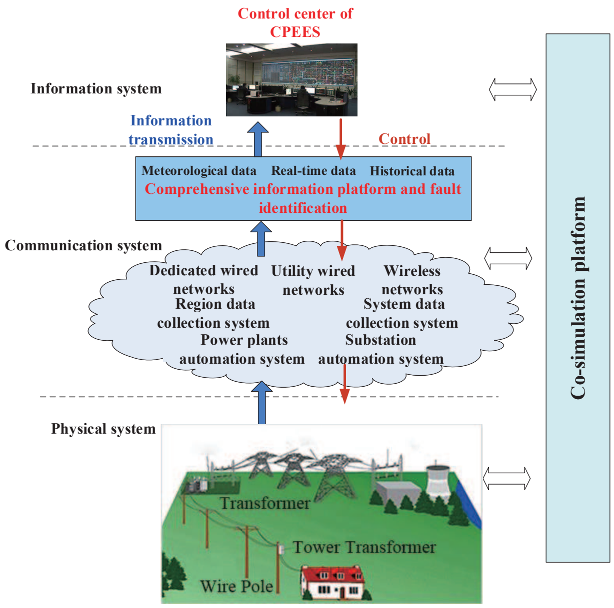

Fig. 1. The architecture for CPEES.

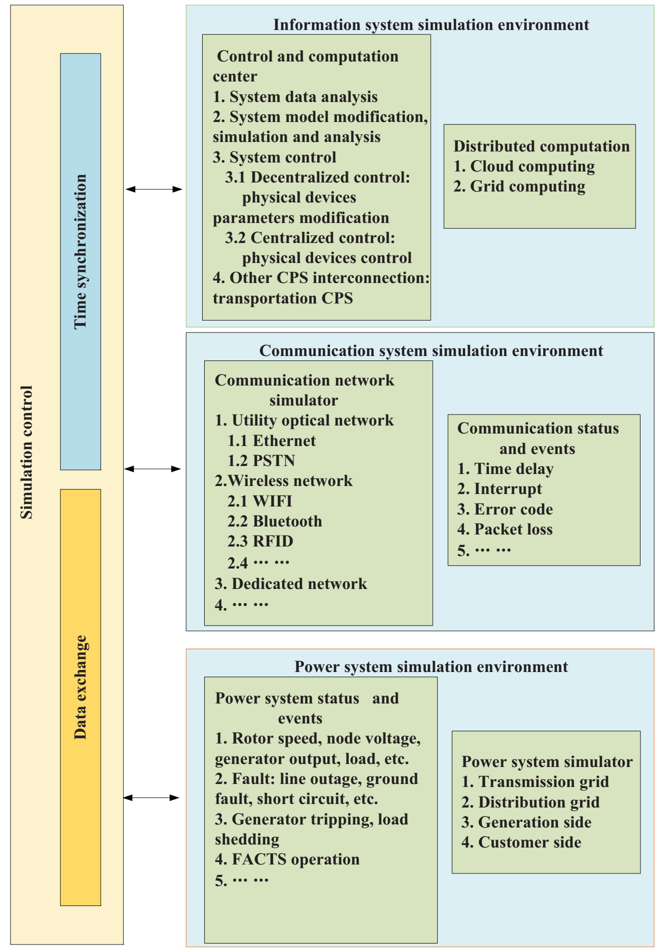

Fig. 2. Co-simulation architecture for CPEES.

of CPEES. Currently, both the power and the communication systems are analyzed by using separate simulators. Simulating the whole CPEES can only be achieved by either re-implementing the communication models in power system simulator (or vice versa) or establishing a co-simulation platform which combines both simulators and uses simulation control module to realize time synchronization and data exchange. Although the re-implementation has no need for time synchronization and data reconstruction, power system simulator usually cannot support exhaustive functions needed by the communication system modeling or vice versa. In [4], an integrated development platform was set up in communication simulator OMNeT++. The power system was modeled in MATLAB and then linked into OMNeT++. The platform accomplished power flow calculation and static power system analysis. Due to the limitation of simulator, it is difficult for dynamic power system simulation.

Co-simulation, combing with different simulators by means of simulation control module, is an efficient way to analyze CPEES, which is able to simultaneously simulate dynamics of power system and information communication system. Experts from power system and information communication technology (ICT) can utilize their preferred simulator rather than fresh and unfamiliar one. By directly using dedicated & available libraries, simulation accuracy and efficiency can be ensured [5].

The architecture of co-simulation mainly contains the following four parts: power system simulation, information system simulation, communication network simulation and simulation control module, as illustrated in Fig. 2. The power system simulation is developed to account for relevant components interacting in the operation of power system. The information system simulation mainly contains two functions, that is to say, data analysis & computation, and system control & protection. The imitation of practical communication network, which exchanges data between power system and information system, is completed by communication network simulation. The simulation control module is used to realize the coupling between different simulators by defining data exchange and time synchronization mechanisms.

A. Power System Simulation

In co-simulation, power system simulation sends system states and events, such as rotor speed, node voltage and fault, to information system via communication system, meanwhile, receives control comments to regulate system operating condition. Commonly used simulation tools are DIgSILENT Power Factory [6], PSCAD [7], MATLAB [8], Adevs [9], Modelica [10], OpenDSS [11], PSLF [12], OPENDSS [13], [14], VTB [15]–[17]. In [6], for real-time evaluation of cyber-physical energy system, a co-simulation environment INSPIRE has been established and DIgSILENT Power Factory is employed for simulating the electromechanical dynamics of power system. In [7], for evaluation the outcome of proposed communication strategy on fault monitoring of power system, the IEEE 13-node test feeder model was set up within PSCAD. To evaluate the performance of wide area damping control of power system, an IEEE benchmark test system was modeled in MATLAB in [8].

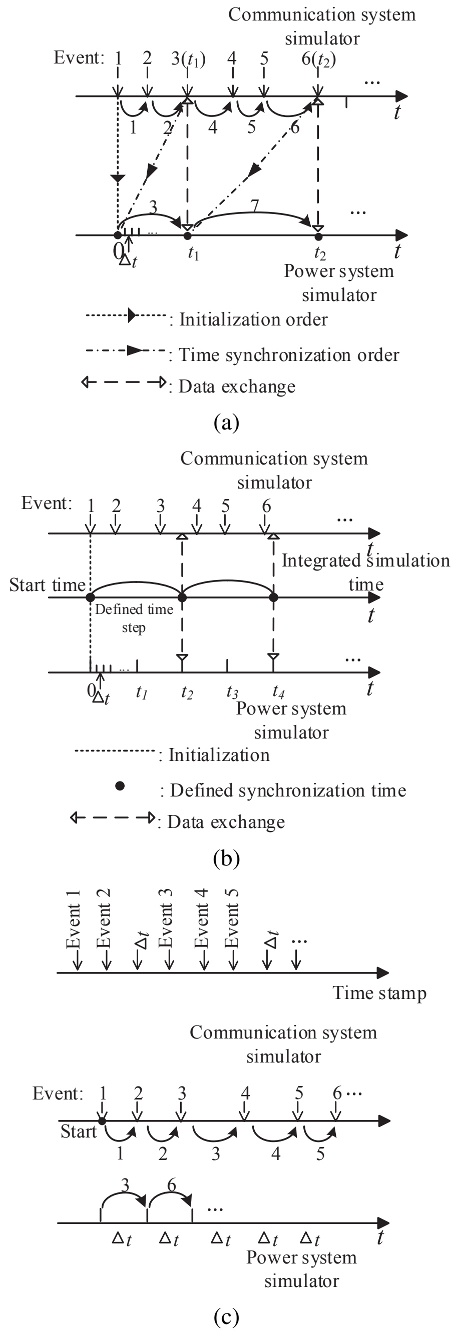

Fig. 3. Synchronization methods. (a) Master-slave synchronization method; (b) Time-step synchronization method and (c) Event-driven synchronization method.

B. Communication System Simulation

Communication system simulation environment imitates the practical communication network, which is in charge of data exchange between power and information systems, by modeling network topology, communication protocol, and so on. In addition, various events such as time delay, error code and packet loss, are simulated as stochastic failure and safety problems, which can be used to analyze the impact of information flow on power system. Commonly used communication network simulators are NS-2 [9]–[12], [18], OPNET [14]–[17], [19], [20], and OMNET++ [4], [13].

C. Information System Simulation

In CPEES, information system has functions of data analysis, model identification, algorithm generation of system control & protection as well as distributed computation. Unlike the traditional dispatching center where control and monitoring functions stay at the centralized level, the information system in CPEES works both at decentralized and centralized levels [21], [22]. All functions can be modeled in various software tools such as MATLAB/SIMULINK [23], Microsoft Visual Studio [8] and JAVA-based agents [24].

D. Simulation Control

Normally, power system simulator is time-driven, while communication system simulator is event-driven; hence time synchronization and data exchange are the key challenges for CPEES co-simulation. At present, there are three synchronization methods, i.e., master-slave [4], [10], [13], [20], time-stepped [15]–[18], and global event-driven methods [9], [12], as shown in Fig. 3 [25]. In master-slave method, master simulator coordinates the co-simulation. During co-simulation, master simulator has higher priority and sends time synchronization comment to slave simulator, when data exchange is needed. Either the power system simulator or communication simulator can be regarded as the Master. Communication system simulator is the master in the figure. In terms of time-step synchronization method, simulators run their simulation independently and only pause at the defined synchronization time to exchange data. In terms of event-driven synchronization method, a global event list is prepared, and according to their timestamp, simulators run orderly.

III. The Interaction between Power and Information Flow

A. Interaction Mechanism

Since the power, the information and the communication systems are integrated into a hybrid system, the interaction among these systems has to be considered carefully for the CPEES. More and more renewable power generations, flexible loads are being connected with power grid, which significantly speeds up the dynamic process of power system control. In order to realize efficient power system control, the assistance from ICT is indispensable.

The information infrastructure over the last decades has contributed to the economic and secure operation of power grid. Because operators have comprehensive knowledge on the state of the system and the ability to rapidly respond to disturbances, power system is possible to operate with smaller security margins. This can significantly reduce operation cost. The robustness of power system is also increased by the improvements in monitoring, control and protection tools.

However, questions have been raised about the interaction between power system and ICT when faults happen in any of them, as illustrated in Fig. 4. Literature [26] summarized some of most important ICT failures and their effects. When power system faults happen, there is huge data needed to be collected by control center, including node voltages, power

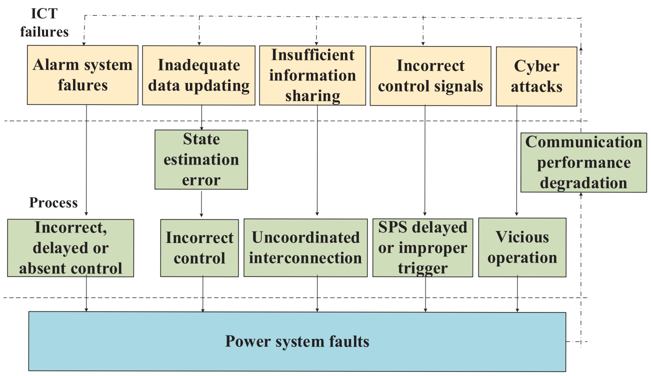

Fig. 4. Interaction between power system and ICT.

flow on transmission line, flexible load states, etc. The communication network performance will be affected by the boomed communication traffic, which results in increased packet loss and time delay as well as decreased transmission rates. This will degrade data exchange between power system and ICT, and lead to ICT failures reversely.

B. Analysis Methods

CPEES are an integrated system of power and ICT and couple continuous dynamic and discrete event-based systems. For continuous system, its analysis and modeling methods are based on continuous mathematical theory, and differential, algebraic equations are often used for system modeling. However, for discrete system, discrete mathematical theory is its basis and the common modeling tool is finite automation. Since the theoretical basis, modeling tools of power system and ICT are obviously different, together with the uncertain interaction between systems, they are major challenges for system modeling CPEES. At present, there are the following three analysis methods: dynamical modeling, coupled network modeling and real-time co-simulation, to investigate the above interaction between power system and ICT.

Table I shows the advantages and disadvantages of these methods. For the dynamical modeling method, it is important to establish the mathematical formulations of both the information and the power flow. Based on this, the system characteristics such as stability, controllability and observability can be investigated. In [27], an unified modeling method was proposed based on mathematical tools such as differential-algebraic equations, finite automation, stochastic process, queueing theory and so on. Moreover, the information flow model considers various ICT devices such as router, communication line and sensor units.

The statistical properties of power and information systems should be analyzed before the coupled network modeling. The

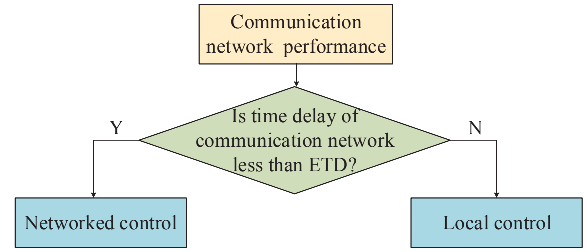

Fig. 5. Schematic diagram of networked and local combined control.

properties include failures in time rates, mean time between failure values and transition time, and the finite time necessary for events to occur. Based on the statistical properties, the coupled network model of power and information systems is established to investigate the infrastructure interactions. However, the time-consuming modeling process is main problem, because of the necessity of clarifying static statistical properties and coupled relation of each device in power and information systems. In [28], a method using marked Petri net models was proposed to simultaneously model the power and the telecommunication infrastructures. The established model can be used to analyze how events in the communication infrastructure interact with the power infrastructure and result in power blackouts.

The real-time co-simulation, discussed in Section II, can be used to study the interdependencies of the power and the information systems, and to investigate the stability of power system and the evolutionary process of the system vulnerability. By deriving mathematical expression of various events emerging forms in the power and the information systems and quantitative index of vulnerability, the influence of emerging forms on system stability can be evaluated during the real-time simulation. But as power and information software of modeling, analysis are indispensable, the ability of cross-discipline software utilizing is the main challenge. Various co-simulation frameworks were proposed in [4], [9]–[20]. Features of the above three analysis methods are summarized in Table I.

IV. Power System Control and Protection in Information Network Environment

In the context of information network, the networked control can be used with the sufficient utilization of global system information to achieve stable and efficient operation of power system. However, control devices have to face problems of uncertainty in time-delay and information path. These problems affect the controllability and observability of system, which even lead to instability and collapse of whole system [29]–[31]. Networked & local combined control [32], and time-

TABLE I
Comparison of Different Analysis Methods

Analysis methods	Advantages	Disadvantages
Dynamical modeling	Theoretical study	Model mismatching problem
Coupled network modeling	More details on interaction	Time-consuming modeling process
Real-time co-simulation	More details on evolutionary process of system vulnerability	Software utilization of cross-discipline

delay & data-loss compensation control [30], [31] are two main solutions.

For the networked & local combined control, when identifying that the communication network will degrade the performance and reliability of networked control, and the performance of local control is better than that of networked control system, the local control can be activated, which only needs local information and reduces the demand on communication network. In [32], an allowable time delay named equivalent time delay (ETD) was proposed for the ICT infrastructure, as shown in Fig. 5, which means the performance of networked control with the ETD is equivalent to that of local control. Therefore, only when the total time delay in the networked control is less than the ETD, the networked control is used.

For the time-delay & data-loss compensation control, one most used principle is to adopt receding horizon optimization to compute control signals of current and future several time intervals for controllable devices [27]. When actuators cannot receive current control signal due to information network problems, they perform predicted control signals received before.

In addition, power system networked control aims at achieving global optimal control. Since there are a large number of physical devices in CPEES, it is impractical to achieve global optimal control by centralized control. The distributed coordination control, as shown in Fig. 6, is an efficient way. The bi-directional information can be used to trigger orderly interaction and active control of customer, industry and distributed energy resources (DERs). Together with the coordination between distributed control and protection devices (CPDs), which have functions of communication and distributed computation, the economical network reconfiguration as well as fast fault location, isolation and restoration can be realized with the target of minimizing the area of power blackout.

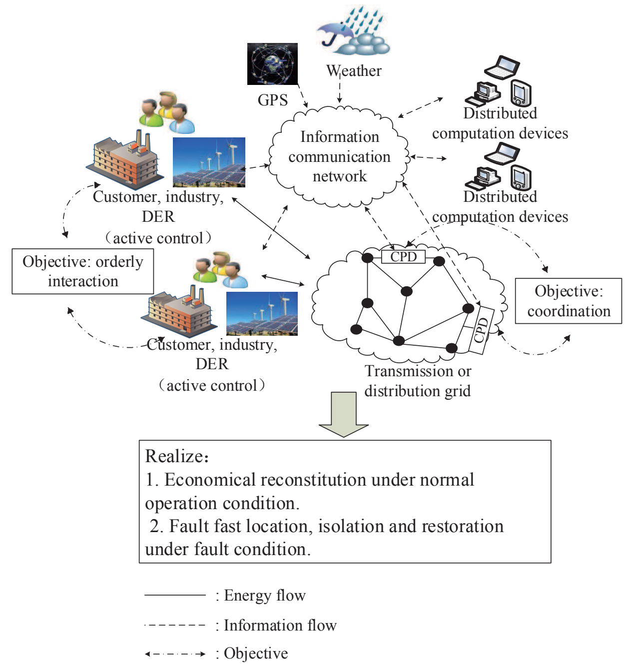

Fig. 6. Distributed coordination control concept in CPEES.

V. Other Aspects

A. Mass Data Processing and Cluster Analysis

By means of mining mass data of CPEES, the multi-dimension analysis seeks latent variables which determine the distance between objects. Moreover, these variables are shown by form of graphics in low-dimension space, realizing the identification and assessment of secure operating region, critical region of instability and fault operation region of power grid. In this part, the following issues also should be paid attention: 1) fault information transmission mechanism in temporal and spatial multi-dimensional scale; 2) fault feature mining and interference signal identification theory; 3) detection method of latent and high resistive faults, and faults accurate location theory.

B. Architecture of Communication Network

As shown in Fig. 7, the architecture of communication network is a star-mesh and level combined one. The architecture can be divided into three levels: plant/substation, region and system levels. In each level, the star-mesh network is adopted to consider the reliability and economy. The lowest level consists of power plants, substations, smart loads, and control & protection devices and takes the responsibility to collect real-time data, and perform control & protection. The regional control center in the second level aims at the control and protection in its region, and exchanging data with the system control center. The top level is the system control center, which collects, analyzes system data and coordinates each control substation to realize the global optimization.

Totally, there are three types of communication networks, i.e., the dedicated wired, the utility wired and the wireless networks [33]. Dedicated wired network has advantages of low time delay and high transmission reliability, and can be adopted to connect control center with critical sensors and control devices. Considering the economy of communication network, the utility wired network should also be considered. But for the problems of time delay, packet loss and so on, it should be in charge of the communication of non-critical devices, like computation and backups devices. The wireless network is a feasible way for mobile components of system, like electric vehicles (EVs) and devices where the communication wire is hard to access [34].

C. Information Transmission Technology

With the development of CPEES, more and more devices will be involved in future. Therefore, the communication traffic is inevitably increased. Due to the capacity limitation, the increasing communication traffic gives rise to network congestion and degrades the transmission performance of network, which result in transmission speed decline and time delay increase. Thus, it is necessary to investigate the congestion and traffic control, and equilibrium approach of real-time information flow. Information scheduling approach should be formed to address the soar in communication traffic, when faults or other urgent cases happen in grid. Besides, the

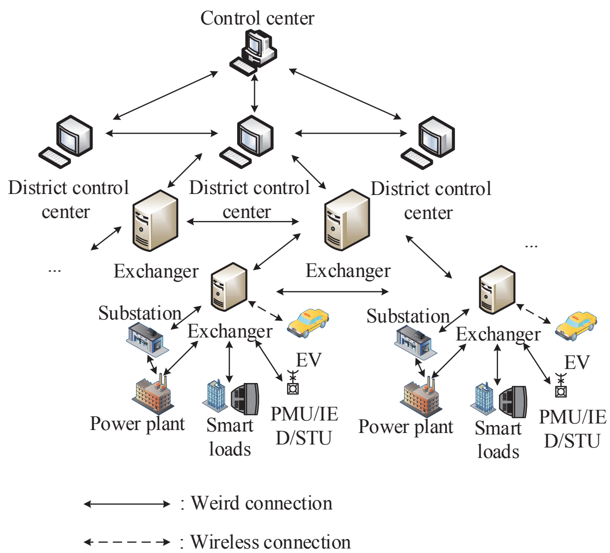

Fig. 7. Communication network architecture.

information security and defense mechanism, communication protocol, network standard and compatible information model for various devices are other fields should be focused on.

D. Security of CPEES

Because CPEES are a physical and information coupled system, the security of CPEES should consider both physical and information systems. Besides traditional security problems of power system, such as transient stability, angle stability, security problems of information system in information communicating, processing, decision-making process and so on should also be paid close attention to. Moreover, due to the close interaction between physical and information systems, the security problems of power and information systems are not independent [35]. Faults in information system will influence the security of power system or vice versa, for example, an attack which falsifies the data communicating in information system will make CPPES do a wrong control decision which damages the security of power system. [36], [37] did some work in power and information systems security. However, the correlation of security of power and information systems have not been exhaustively researched. Hence, it is necessary to establish the power and information combined security theory for CPEES.

VI. Conclusion

Cyber-physical electrical energy systems are a kind of new-type system, which integrate power and information systems. By the fusion of power, information and control, the safety, reliability and efficiency of power system can be improved. However, CPEES are a new research field, there are critical scientific problems and technologies. For the simulation & evaluation of CPEES, co-simulation is an efficient way which directly uses dedicated & available libraries to ensure simulation accuracy and efficiency. This paper overviews various simulators used in the power, the communication & the information systems and synchronization methods in simulation control. Since CPPES is a highly integrated system, the interaction between power and ICT, especially, the interaction when faults happen in any of them, has to be considered carefully. Therefore, the interaction mechanism and analysis modeling methods are analyzed and summarized. In the context of information network, stable and efficient operation of power system can be achieved. However, the uncertainty in ICT should be considered in the power system control and protection. In order to address the uncertainty, two main solutions, i.e. networked & local combined control and time-delay & data-loss compensation control, are used. Moreover, problems of mass data processing and cluster analysis, architecture of communication network, information transmission technology and security of CPEES are also summarized and analyzed in this paper. By solving the above problems and technologies, the development of CPEES will be significantly promoted.

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