Research on Collaborative Real-Time Simulation Technology of Multi-Energy Complementary Integrated Energy System

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Abstract. In order to realize the real-time simulation of regional integrated energy system, a multi-energy flow collaborative real-time simulation technology based on message bus is proposed, and the real-time simulation platform established on this basis realizes the real-time simulation of electrical and thermal systems. By using the co-simulator composed of message-oriented middleware and adapter to coordinate multiple simulators to complete the real-time simulation of the system in the loop, the message bus uses the open source ZeroMQ; it provides a unified message subscription and message publishing mechanism for all real-time simulators. Adapters are used to connect a variety of heterogeneous emulators, such as RT-LAB, TRNSYS, etc., to messaging middleware. Adopting message-oriented middleware and adapter scheme, it has the characteristics of open and extensible. The simulation system developed in this paper can be used in the real time simulation of distribution integrated energy system to realize the interaction between energy flow and information flow.

Keywords. Integrated energy system, collaborative real-time simulation, message bus, messaging middleware

1. Introduction

With the increasing demand for energy from industrial production and people’s life, the contradiction between energy utilization and ecological environment becomes increasingly prominent. At present, traditional energy systems are independent and inefficient in energy use. Integrated energy system (IES), which integrates electricity, heat, cold and gas, has been widely concerned in the world. The complementary integration of different types of energy not only improves the efficiency of energy utilization and the absorption capacity of renewable energy, but also provides a new perspective for energy analysis and drives the integration and innovation of multi-fields, multi-disciplines and multi-dimensions [1-3].

Due to the complex structure and diverse operation modes of integrated energy system, it is difficult to use physical experiments to study its coupling dynamic

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characteristics, and the related technology and product research and development lack a more real test and verification environment. Digital time domain simulation becomes a necessary technical tool for the planning, design and operation control of integrated energy system [4]. However, based on the status quo of energy utilization, the simulation analysis of each energy subsystem is also independent that there are two problems [5, 6]: (1) From the perspective of optimizing operation, cannot establish a comprehensive optimization goal can flow, not consider other energy subsystem, the internal constraints of cannot establish the whole system of complete and accurate to the feasible region. (2) From the perspective of safe operation, the dynamic interaction and risk propagation process between subsystems cannot be accurately simulated. In order to solve the above and other problems, the corresponding real-time simulation platform of integrated energy system with multi-energy complementarity is developed as a support, which is helpful to study the mechanism of multi-energy coupling and describe the complex dynamic process of multi-type energy conversion and coupling network.

Experts at home and abroad have done a series of research work on the co-simulation and optimization of integrated energy system. In China, the research on collaborative real-time simulation of integrated energy started late, and most of the research on integrated energy system focuses on off-line simulation and optimization planning. Reference [7] proposed the co-simulation architecture of electricity, heat and gas combined power flow based on message bus. The established time synchronization rules of integrated energy co-simulation support multi-energy flow time series power flow calculation and realize the convergence of co-simulation. Reference [8] proposed a dual-time scale co-simulation framework that combined the slow time scale characteristics of the natural gas dynamic transmission model with the fast time scale characteristics of the dc power flow model of the power grid, and studied the bidirectional propagation mechanism of interlocking faults between the electrical and gas subsystems and their interaction effects. Reference [9] developed the modeling and simulation tool CloudPSS, which combined with comprehensive analysis tools such as Internet, cloud computing and artificial intelligence to provide users with modeling and simulation analysis functions for a variety of energy networks. In Reference [10], the energy flow model of the triple power supply system was established based on the energy hub, and an energy flow calculation method of the electric-gas coupling micro-energy network was proposed. The comprehensive simulation of the micro-energy network with CCHP was carried out on the platform of OpenDSS and MATLAB. Reference [11] established a unified modeling and simulation platform for integrated energy system, and proposed a cross-platform joint digital simulation technology scheme. TRNSYS and MATLAB/Simulink are selected to construct the integrated energy co-simulation platform to meet the deep simulation requirements of integrated energy. In foreign countries, the development of collaborative simulation platform is more in-depth, but there are few collaborative real-time simulations involving integrated energy system. GridSpice [12] is a distributed co-simulation platform based on cloud platform developed by Stanford University, which can integrate power system generation/transmission/distribution/marketing and other applications, mainly used for smart grid planning, analysis and design. FNCS [13] was developed by the U.S. Northwest Pacific State Key Laboratory (PNNL) and is mainly used for the co-simulation of power system and communication system, but the comprehensive simulation of multi-energy flow and real-time simulation scenarios are not considered. VOLTTON [14] is a collaborative simulation platform developed by PNNL and funded
by the Office of Building Technology of doe, which adopts message bus architecture. However, due to its concern on the time scale of demand response, the real time degree is very low, which cannot meet the needs of integrated energy system co-simulation. FMI/Modelica [15] is an open, object-oriented modeling language based on differential algebraic equations, which can support the modeling of complex physical systems in multiple fields. The simulation module that implements FMI/Modelica standard is called FMU. A large number of collaborative simulation systems have been developed based on this standard. In summary, on the one hand, the existing co-simulation technology is mainly offline simulation, and rarely involves real-time co-simulation technology. On the other hand, it still focuses on power system and rarely involves the co-simulation of integrated energy system.

In view of the current technical situation, this paper proposes an open and extensible real-time co-simulation scheme of regional integrated energy based on message-oriented middleware. The established real-time simulation platform realizes the real-time simulation of electricity and thermal system, provides a support platform for solving the technical difficulties in regional integrated energy demonstration and application, and also provides feasible real-time simulation solutions for other integrated energy technologies.

2. Function Analysis

The construction route of integrated energy system simulation platform can be divided into integral simulation method and cooperative simulation method. The former refers to the establishment of integrated model of multi-energy flow system and simulation calculation, while the latter realizes system-in-loop simulation through the cooperation of multiple simulation systems. The co-simulation method is adopted in this paper because: (1) There are many mature simulation software and platforms in the fields of electricity, heat and gas; (2) In reality, only weak coupling exists between subsystems of energy flow; (3) The physical characteristics and response time of each energy flow system are very different. By using the co-simulation technology, the existing mature simulation system can be continuously utilized, and the weak coupling characteristics between the systems can be fully utilized to optimize the overall performance of the simulation system.

Existing co-simulation mainly focuses on the following aspects: (1) Information physical system (CPS) simulation, mainly focusing on the co-simulation of power system and communication system; (2) Transmission grid-distribution network (T&D) co-simulation, mainly focusing on the interaction between the power price of transmission grid nodes and the interactive users of distribution network; (3) The co-simulation of electromagnetic transient and electromechanical transient, mainly focusing on the co-simulation of large power grid dynamics and local power grid electromagnetic transient [16]. Compared with the requirements of this project, the existing co-simulation technology has two short comings: (1) it is mainly offline simulation and rarely involves real-time co-simulation technology; (2) It still focuses on power system, and rarely involves co-simulation of regional integrated energy system.

As for the real-time simulation platform architecture, it is generally required to have the following characteristics, and the research in this paper is based on these characteristics.
• Openness: An open co-simulation scheme based on message-oriented middleware is proposed. Message-oriented middleware provides message management mechanism and time synchronization mechanism, and supports plug-and-play of emulators;

• Heterogeneity: Develop co-simulation adapters to support co-simulation of heterogeneous real-time simulators such as RTDS or RT-LAB and independently developed simulators [17];

• Multi-energy flow: Support the co-simulation of cold/heat/electricity/gas multi-energy flow system;

• Scalability: The scale of co-simulation can be dynamically adjusted, supporting no less than 10 real-time simulators;

• Real-time: Co-simulation does not affect the real-time performance of each simulator; The co-simulator can be implemented based on a general computer platform, and the simulation step length at the collaborative level is at least 1s, which meets the simulation requirements of optimal operation, safe operation and dynamic analysis at the system level;

• Interactivity: Electrical communication and interaction can be realized between the independent platform and RTLAB/RTDS platform.

3. Architecture of Co-simulation

Figure 1 shows the complete configuration and overall architecture of the collaborative real-time simulation system. In practice, the system structure can be adjusted according to the needs of simulation. We use the developed co-simulator to coordinate multiple simulators to complete the system in-loop simulation. The co-emulator consists of message-oriented middleware and adapters. Message middleware provides message management, time synchronization and other mechanisms. Message bus uses open source ZeroMQ to provide a unified message subscription and message publishing mechanism for each real-time simulator. The adapter is used to connect a variety of heterogeneous emulators, such as RT-LAB, TRNSYS, GridLab-D, etc., to message-oriented middleware. Due to the large inertia of heat/cold and gas energy systems and the slow change of simulation variables such as temperature, air pressure and flow rate, the simulation step size is generally at least second level or even minute level. Therefore, the architecture actually realizes weak real-time simulation, and the main step size of co-simulation is more than 1 second.

Co-emulator refers to the software or device that coordinates multiple emulators. The co-emulator itself does not perform the simulation function of the specific system, but can provide message management, time synchronization and other mechanisms, so that multiple emulators jointly complete system-in-loop simulation (SIL). In this article, the co-emulator consists of message-oriented middleware and adapters. Among them, message middleware is used to realize message management, time synchronization and other mechanisms. Adapters are used to connect multiple heterogeneous emulators (such as RTDS, RT-LAB) to the above message-oriented middleware. The adapter and messaging middleware exchange information using subscribe or publish mechanism. By adopting the architecture of message-oriented middleware plus adapter; the co-simulation system is open and extensible. The main step size of co-simulation has real time advance significance, and its value depends on the change period of system
coupling variable, which is generally much larger than the internal step size of each emulator. For example, in a CHP system, where the coupling variables are the thermal power and electrical power of CHP and the minimum change period is 1 s, the step size of the co-simulator can be set to 1 s.

Figure 1. Overall structure diagram of multi-energy flow joint real-time co-simulation platform.

4. Message Bus-Based Data Interaction

4.1. Message Bus Scheme

To support openness, the message middleware adopts ZeroMQ [18, 19], an open source message bus, to provide a unified message subscription and message publishing mechanism. It abstracts and encapsulates the low-level details of network communication, message queue and threads scheduling, and provides concise API functions to achieve high-performance network communication.

The specific composition scheme based on message bus adopted in this paper is shown in Figure 2. Message bus can be deployed on an independent computer. The Adapter can be configured in three ways: (1) Integration with the simulator; (2) Integration with message middleware; (3) Run on an independent computer.
The specific coordination process is as follows:

1. Set each emulator (or its adapter) to run (or communicate) in real time with phase synchronization, such as 1 s;
2. Set the initial forced synchronization point due to the different clocks and inconsistent starting time of simulation.
3. Send the start signal message (message No. 0), and each emulator enters the first step at the same time;
4. At the $T$ step, each emulator firstly obtains the subscribed (Topic, value) message from the message bus and updates the marginal variable of the book subsystem; then it publishes (Topic, value) messages to the message bus, updating its own state variables. It should be noted that the subscribed message reflects the status of the $t-1$ step of other emulators, and there is a step delay;
5. Continue to run until the end signal is received. Since then, the emulators are no longer coordinated and run independently.

4.2. Interfacing

Simulation interface technology is the key technology to realize co-simulation, which includes equivalent modeling of coupling device, timing sequence of data exchange, data type conversion and so on. In the integrated energy system, heat/cold, gas energy and other systems, due to its large inertia, temperature, flow rate and other simulation variables change slowly, its simulation step is at least second level, or even minute level (hereinafter referred to as slow simulation system); However, simulation variables such as voltage and current instantaneous values in electric power system change rapidly, and their simulation step is generally about 50us (hereinafter referred to as fast simulation system). Each energy flow system is coupled together through gas turbine generator, electric boiler, electric refrigeration, gas boiler and other equipment. In the process of real-time co-simulation, equivalent modeling of coupling device model is required [20].

The coupling device model based on electric power simulation system, the real-time simulation system that is fast model electricity on port voltage current instantaneous value simulation data in situ, waveform features will not be lost, without fast transfer between the system, the system only transfers between thermal power values of slow change, no current instantaneous value from thermal power to voltage data type conversion. At the same time, in the thermal simulation system, the thermal
power value can be converted into temperature and flow rate through the heat calculation formula. For the coupling device model connecting more than two energy flow systems, the process is similar, that is, the model is placed in a fast system for modeling and simulation.

The implementation principle of the TRNSYS adapter is shown in Figure 3. Type155 components provided by TRNSYS are adopted, and Matlab programming is supported, which is the widely used interaction mode between TRNSYS and external applications [21]. At each simulation step size, the adapter is responsible for receiving subscribed external information from the message bus (reflecting the t-1 status of other emulators) and updating its internal variables; At the same time, the message bus sends its own state variables to the outside (reflecting the TRNSYS step T state).

![Figure 3. Interface and principle of TRNSYS adapter.](image)

For RT_LAB, the adapter and RTLAB can be configured independently, and the two can be realized only through standard socket communication. The realization principle is as follows (see Figure 4):

![Figure 4. Interfaces and principles of the RTLAB adapter.](image)

For the time sequence of data exchange, we adopt the following time synchronization mechanism, including:

1. Clock timing: Each emulator uses IRIG-B code or 1588 PTP and other protocols for timing; GPS can be used as the master clock to achieve absolute timing, or one of the simulators can be used as the master clock to achieve relative timing.

2. Message timing: Taking RTDS simulator as an example, message timing is shown in Figure 5. In the figure, RTDS carries out real-time simulation of power system; RTDS and RTDS communication cards are hard real-time simulation, and their overall delay and jitter are less than two simulation steps (about 100us). RTDS adapter and message-oriented middleware run on general purpose computers, which are soft real-time simulation, and their delay is very uncertain, about 1-100 ms. However, since
the RTDS communication card has marked each message with a precise synchronization sequence number (seqNum), data alignment can be achieved. In other words, the sampling time of the message (synchronization sequence number) rather than the arrival time of the message determines the data/event occurrence time, thus eliminating delay and jitter caused by message transmission and processing.

5. Verification of System Platform

Heat fixed by electricity and power fixed by heat are the two most commonly used operation modes in regional integrated energy system. For example, in the northern heating season, ensuring heat supply is the primary indicator, and the thermoelectric system should work in heat fixed by electricity mode. In some peak load hours, when the power supply is insufficient, the thermal system should be operated in fixed-heat mode. The purpose of this study is to verify the correctness of the simulated real time platform for integrated energy system. RTLAB real-time platform will be used for modeling and simulation of electrical part, the simulation model is shown in Figure 6. The CHP model will be simulated by TRNSYS, the simulation model is shown in Figure 7. In the real-time co-simulation step, the simulation of the slow simulation system (TRNSYS) is started by the simulation of the fast simulation system (RTLAB). During the simulation process, each energy flow simulation system interacts with each other through the message bus, and the interactive data includes boundary coupling variable values and simulation results.

![Figure 5. Iterative process of co-simulation.](image-url)
The regional integrated energy system runs normally under the electric fixed heat mode. Under this working condition, although no significant interference is set, the ambient temperature and humidity are in the process of dynamic change, so the regional integrated energy system will also be in the process of dynamic stability. Simulation results of key variables are given below.

Figure 6. Simulation model diagram of RTLAB power system.

Figure 7. Simulation model diagram of TRNSYS-CHP system.
Figure 8. Changes in ambient temperature and mechanical power of gas turbine.

Figure 9. Power output by the CHP system.

Figure 10. Angle difference of grid-connected power in CHP system.
We can see the overall result of the simulation in Figures 8-11, when the regional integrated energy system is in a relatively stable operation state, the mechanical power output and smoke exhaust temperature of the gas engine will be affected with the change of ambient temperature and humidity. The change of mechanical power further leads to the change of electrical power sent to the CHP system, which affects the power Angle difference and voltage amplitude of the connection point. From the perspective of variation trend, the increase of temperature will lead to the decrease of mechanical power, resulting in the decrease of the power generated by the generator, and further lead to the decrease of the power Angle difference. Meanwhile, due to the excitation system, the output voltage of the generator remains stable, but its amplitude also fluctuates slightly, showing a negative correlation with the temperature change.

6. Conclusions

The technical scheme proposed in this paper preliminarily realizes the real-time co-simulation of multi-energy stream based on message bus technology. The established real-time simulation system platform has a certain degree of real time and scalability, and the developed adaptor for different energy simulation system has a preliminary capability of multi-energy real-time simulation. The simulation system can effectively improve the efficiency of integrated energy system planning and design work, and provide technical support for integrated energy system engineering.

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