REAL-TIME DIGITAL CO-SIMULATION METHOD OF SMART GRID FOR INTERGRATING LARGE-SCALE DEMAND RESPONSE RESOURCES

Jie SONG
State Grid Shanghai EPRI
songjie@sh.sgcc.com.cn
Jian ZHOU
State Grid Shanghai EPRI
zhou.j@sh.sgcc.com.cn

SonghanJIANG
Shanghai Jiao Tong University – China
bikong@sjtu.edu.cn

Peichao ZHANG
Shanghai Jiao Tong University – China
pczhang@sjtu.edu.cn

ABSTRACT

With study of activating the immense potentials of demand response (DR) in load side attracts widespread attention, a simulation platform with the ability of "Source-Grid-Load" interactive operation is essential. Nevertheless it's an enormous challenge to incorporate the DR resources in real-time simulation as the characteristics of mass, diversity and responsiveness. This paper presents a method of digital real-time co-simulation (DRTCoS) applied to smart grid integrated with large-scale DR resources. Firstly, the strategy that decoupling the network with DR resources from the rest parts according to different dynamic responses is proposed, building the multi-rate digital simulation, and an interface algorithm for the co-simulation is devised. Then DRTCoS that combines Real Time Digital Simulator (RTDS) and the power distribution system simulation, GridLAB-D is built, with typical application scenarios on micro-grid and high-voltage grid studied. Finally, case study validates the effectiveness of the co-simulation based on large-scale air-conditioningloads.

INTRODUCTION

With the ability of simulating real operating environment of power system, supporting cyber system in-the-loop simulation,digital real-time simulation (DRTS) can be used for the analysis, design, and testing of the electric power system and its apparatus[1]. In the field of smart grid operation and control, the typical applications of DRTS include generation scheduling and demand side management[2], coordinated control of distributed energy storage system[3],cyber-physical research of grid[4]. It's essential to simplify the simulation model equivalently for the prominent contradiction between simulation scale and model accuracy in DRTS.Due to the low proportion of flexible load and slow demand response (DR) process, the enormous loads are usually equivalent to the ZIP model[5].

However, fast DR of loads receive widespread attentions recently. Researchers want to activate the potentials of fast DR in loads using relatively low investment to enhance the source-load interactive ability when renewable energy connect to grid on the premise of customer electricity satisfaction.Thermostatically controlled loads clusters are used to smooth micro-grid tie-line power instead of battery storage is introduced in [6].A large number of HVAC loads providing load balancing service, automatic generation control (AGC) are discussed in [7], [8].The research mentioned above require fast interaction ability between grid and load that can be simulated accurately from second to minute scale, however, traditional passive load model can't meet the need. It's necessary to build a new model on DR resource in grey-box modeling framework, in order to reflect user's personalized DR control strategy exactly and simulate the dynamic physical process of load control, which have the ability of dynamic simulation and fast response integrated with large-scale fast response. For example, equivalent thermal parameter (ETP) model for thermostatically controlled loads is a typical grey-box model [5].

Nonetheless, it will cost a large amount of computing resources considering large-scale DR resources of grey-box modeling in DRTS system, due to the simulation step of DRTS is far less than the DR resources dynamic process. The simulation efficiency will be very low if simulating integrated large-scale DR resources and grid. Therefore, this paper presents a method of digital real-time co-simulation (DRTCoS). According to the different dynamic responses, the network with a large number of DR resources is decoupled from the rest of the grid, building the multi-rate digital simulation using computers and special simulation device. An interface algorithm including loop control is designed to exchange information between subsystems. Then research on large-scale fast DR resources participating in real-time dispatching and control using existing DRTS resources is developed. This paper extends the simulation ability of existing digital real-time simulation systems for large-scale fast DR resources using personal computers, which shows the excellent scalability and efficiency of the proposed method.

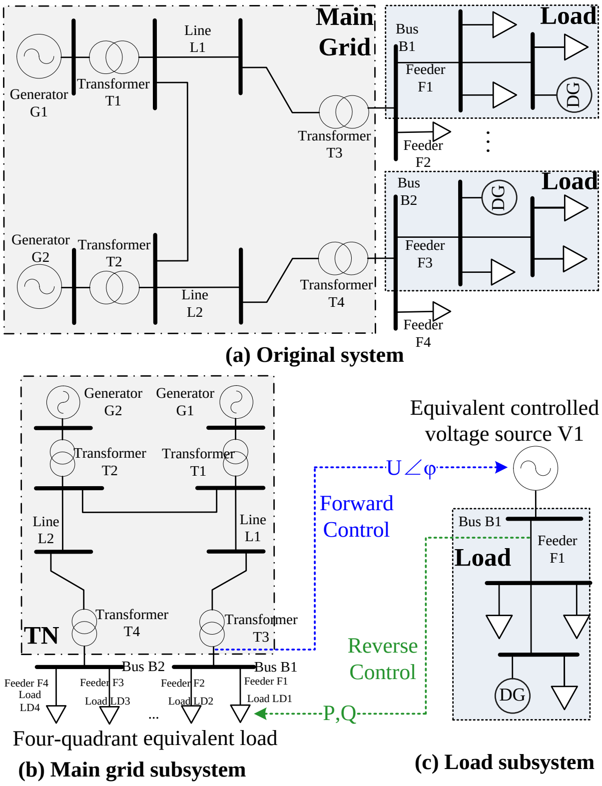
DIGITAL REAL-TIME CO-SIMULATION METHOD

Decoupling method

The part of grid that this paper focuses on is defined as main grid subsystem, the lower feeder is called load subsystem. Taking Figure 1 as an example, this method chooses low voltage bus of main grid distribution transformer as decoupling points, such as Bus B1, B2, decoupling original system as main grid subsystem and multiple load subsystem including DR resources.

Main grid subsystem after decoupling is shown as in Figure 1(b). The distribution part below decoupling points is simplified as four-quadrant equivalent loads, as LD1~LD4. Main grid is simulated in DRTS system,

using time-domain simulation method, the time-step is less than 0.1 millisecond.
Load subsystem after decoupling is illustrated as in Figure 1(c). The main grid part above decoupling points is equivalent as controlled voltage source, as V1. Different load subsystems can be allocated to the multiple parallel simulation general computer.
What's more, the voltage grade of main grid is not qualified, which can be a micro-gird, distribution network or high-voltage power grid.



(a) Original system

(b) Main grid subsystem **(c) Load subsystem**

Figure 1. Decoupling method by network partition

Interface algorithm

As illustrated in Figure 2, interface algorithm is used in coupling multiple subsystems to achieve collaborative, closed loop simulation, which contains the forward and reverse control subsystem.

Forward control subsystem

Using bus voltage as interface variables, forward control subsystem transfer data from main grid subsystem to load subsystem, which are described as follows:

1) Extract three-phase voltage phasor based on three-phase voltage sampling values of main grid subsystem decoupling points bus, such as Bus B1 in Figure 1(b).
2) Transfer three-phase voltage phasor to load subsystem to control the controlled voltage source which realized by swing node, such as voltage source V1 in Figure 1(c).

Reverse control subsystem

Transferring simulation results from load subsystem to main grid subsystem, reverse control subsystem constitutes a closed-loop simulation with forward control subsystem. Reverse control subsystem use feeder's power as interface variables, which are described as follows:

1) Calculate active and reactive power of load subsystem decoupling points bus feeder, like feeder F1 in Figure 1(c). Power is obtained by load subsystem load flow calculate.
2) Transfer active and reactive power to main grid subsystem, to control the four-quadrant equivalent load, like load LD1 in Figure 1(b). Loads in smart grid may be prosumers, so the equivalent loads should have four-quadrant operation ability.

Communication subsystem

As shown in Figure 2, DRTS device send interface variable exchange requests periodically, and communication subsystem listen to the requests and complete the two-way data exchange. To ensure the generality of this method, general Ethernet protocols are used in data exchange, which don't need special requirements for DRTS system. Communication subsystem runs on personal computers

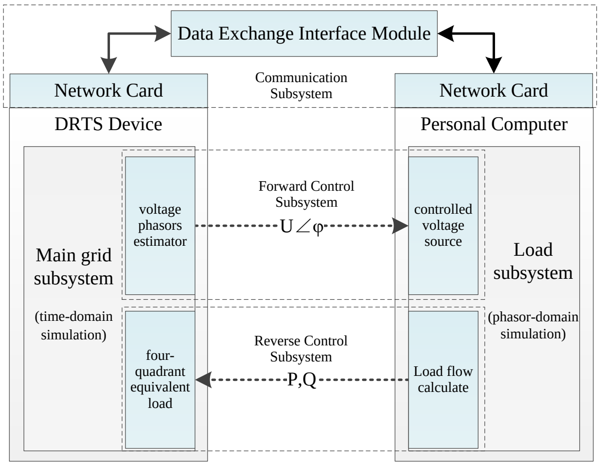


Figure 2.Schematic of the DRTCoS system

APPLICATION SCENARIO ANALYSIS

Currently common used DRTS system is RTDS[9] and RT-LAB[10], and RTDS is chosen as the DRTS system to be used in main grid subsystem simulation. Distribution network simulation software Digsilent[11], GridLAB-D[12] can be used in load subsystem. GridLAB-D is an open source software developed by the U.S. Department of Energy (DOE) at Pacific Northwest National Laboratory (PNNL), and its significant advantage is adding new DR resource models by secondary development. Therefore GridLAB-D is used in load subsystem simulation. Developed by Python, communication subsystem communicates with GridLAB-D using HTTP protocol and communicates with RTDS using socket. The communication cycle is 1 second.
Typical application scenario of DRTCoS system on micro-grid and high-voltage grid will be analysed below.

Smoothing power fluctuation of micro-grid tie-line with thermostatically controlled loads

Intermittent power supply will lead to frequent fluctuation of the interaction power between micro-grid and distribution network, influencing the stability of power system and power quality. At present the expensive energy storage devices are widely used to reduce the grid-connected power fluctuations. In recent years, researchers have focused on the use of large-scale thermostatically controlled loads such as air conditioners (AC) and heat pumps, which can be easily transformed to virtual storages of low cost and fast response speed by certain control method, therefore the energy storage devices capacity and investment will be reduced.

The DRTCoS system structure of the application scenario mentioned above is shown in Figure 3. Analogue output card, GTAO [9] is used to collect the tie-line voltage and current signals by micro-grid controller, and tie-line power is also calculated. Afterwards low-pass filter of different cut-off frequency is used to deal with tie-line power. The high frequency component whose wave period is less than 1 minute is assigned to the power energy storage such as supercapacitor energy storage to mitigate. The low frequency component whose wave period is more than 1 hour is allocated to energy storage such as battery energy storage to mitigate. Moreover the most concerned intermediate frequency component is for AC clusters to smooth tie-line power. It's significant to reduce the energy storage devices capacity and charge-discharge cycles, improve the economic benefit of this application.

After receiving suppression instruction from micro-grid controller, energy storage controller send firing pulse to RTDS through high-speed on-off digital input card, GTDI [9], achieving energy storage control. AC cluster controller allocates suppression instruction to the AC in the community based on transactive control method [13].

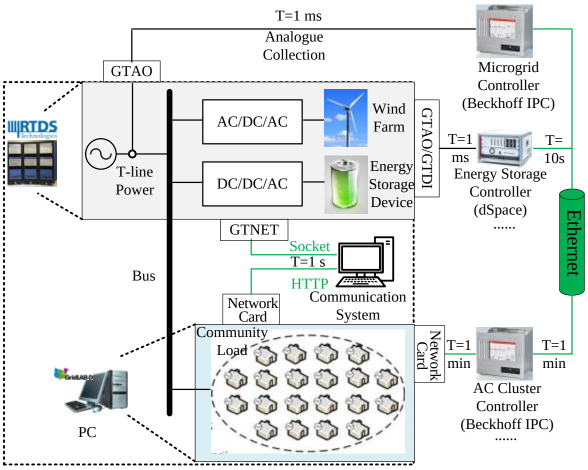


Figure 3. Application case 1: Smoothing power fluctuation of micro-grid tie-line with thermostatically controlled loads

<u>Real-time dispatching by aggregation of massthermostatically controlled loads</u>

Shanghai Chongming Grid contains a 400 MW gas-steam combined cycle power plant (CCPP) and two wind farms whose total capacity is 108 MW, connecting to Shanghai Grid through tie-line. In [14], the concept of wind-gas coordinating equivalent power plant (WGPP) is proposed to implement power system dispatch of renewable energy, where the clean energy wind and gas is regarded as a whole to track dispatch plan. However, CCPP unit need more reserve capacity to response to the variability and intermittency of wind power, which will increase the generation cost.

This paper further extends the concept of WGPP, and thermostatically controlled loads which are regard as virtual power plant, will participate in WGPP dispatch. The developed DRTCoS system is shown in Figure 4.In day-ahead scheduling stage, tie-line power schedule curve is created based on day-ahead forecast. In real-time dispatch stage, rolling forecast wind power of next 5 minutes, and allocate the power adjustment quantity, which is the difference of day-ahead forecasting and super short-term forecasting, to multiple air-conditioning (AC) clusters. When the adjustment is positive, AC clusters will add load, conversely reduce load. Reducing the randomness of wind power by source-load interaction equivalently, CCPP unit can reduce the reserve capacity and the regulation of base power output, which can improve power generation efficiency and enhance tracking schedule curve ability of WGPP.

WGPP real-time dispatch module communicate with RTDS communication card GTNET using IEC-104 protocol[9]. Community AC loads are controlled by multiple AC cluster controllers, whose adjustment quantity is allocated with the total amount of AC power. In order to improve the tracking precision of AC clusters, the inside control cycle of AC cluster is 1 minute. Special occasions such as wind power suddenly change, active power control can be implemented to wind farms to guarantee WGPP tracking schedule curve ability.

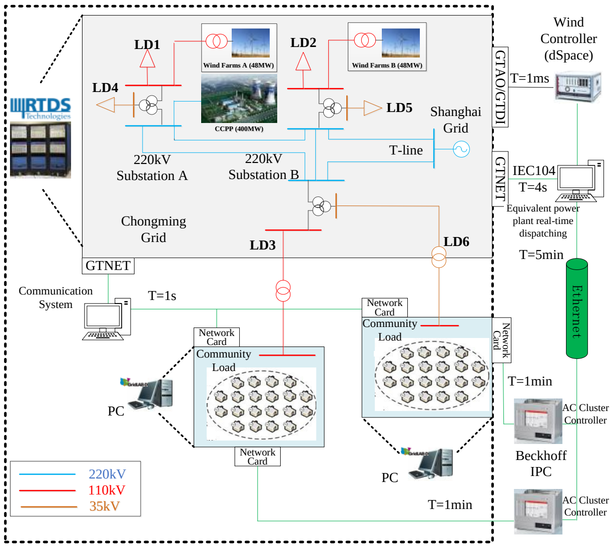


Figure 4.Application scenario: real-time dispatching by aggregation of massthermostatically controlled loads

SIMULATION CASE

As illustrated in Figure 4, DRTCoS system is built based on the application scenario, real-time dispatching by aggregation of mass thermostatically controlled loads. Five community loads are accessed to load subsystem at LD3, LD6 in Figure 4, each load subsystem contains 2000 buildings with AC loads.

AC cluster

AC cluster control

The free load power of AC cluster without any external control is defined as AC baseline power P_{AC}, and power adjustment quantity from schedule is ΔP, therefore the target aggregated power of AC cluster P_{AC}^{*} is given by

$$P_{AC}^{*} = P_{AC} + \Delta P \qquad (1)$$

Transactive control method [13] is used to allocate power adjustment quantity to every AC in AC clusters to achieve target power. A virtual market is established in every AC cluster to accomplish optimal power allocation based on market equilibrium principle.

To measure the comfort levels of customers, state of indoor temperature of AC is defined as:

$$S = \begin{cases} \dfrac{T_{air} - T_{set}}{T_{max} - T_{set}}, T_{air} \geq T_{set} \\ \dfrac{T_{air} - T_{set}}{T_{set} - T_{min}}, T_{air} < T_{set} \end{cases} \qquad (2)$$

where T_{set} is the indoor temperature setpoint, T_{air} is the current indoor temperature, T_{max} and T_{min} is the upper and lower temperature limit allowed by customers. S is normalized value of indoor temperature, and obviously $-1 \leq S \leq 1$.

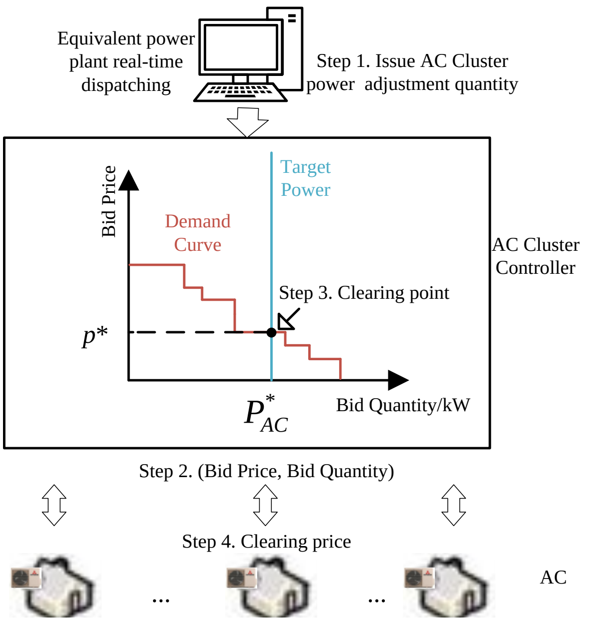


Figure 5. Schematic of virtual market clearing

As illustrated in Figure 5, the allocation strategy of AC cluster aggregated power based on virtual market clearing includes the following stages:

1) Every AC cluster acquires the target aggregated power adjustment quantity from the equivalent power plant real-time dispatching.
2) Every AC bids with its state of indoor temperature, S as bid price, and rated power capacity as its bid quantity.
3) In every control cycle of virtual market, which is 1 minute, AC cluster controller collects the bidding information of every AC, and obtains the demand curve according to the bidding price order from high to low. Based on target power and demand curve, clearing point will be calculated, target power P_{AC}^{*} and clearing price p^{*} will be gathered.
4) AC cluster broadcasts the clearing result, and every AC will receive the clearing price. If the bidding price is greater than clearing price, AC will start work, if not, AC will stop work.

AC cluster parameter settings

Second-order ETP model [5] is adopted for modelling AC loads. Main parameters of AC loads and buildings are shown in Table 1, and U(a,b) denotes the uniform distribution, N(avg,std) denotes the normal distribution.

Table 1. Main parameters of AC loads and buildings

Indoor Temperature Setpoint / °C	Deadband of Thermostat / °C	EER	Window-Wall Ratio
N(26.5,0.5)	U(-1.0,1.0)	U(3,4)	N(0.15,0.01)
House Area/ m^2	Air Change Freq/(Times/h)	SHGC	R_{th} of Roof/ (°C m^2/W)
U(88,176)	N(0.5,0.06)	U(0.22,0.5)	N(5.28,0.70)
R_{th} of Floor/ (°C m^2/W)	R_{th} of Window/ (°C m^2/W)	R_{th} of Wall/ (°C m^2/W)	R_{th} of Door/ (°C m^2/W)
N(3.35,0.35)	N(0.38,0.03)	N(2.99,0.35)	N(0.88,0.07)

EER denotes energy efficiency ratio, SHGC denotes solar heat gain coefficient, and R_{th} denotes thermal resistance.

AC loads are closely related to outdoor temperature and solar radiation environmental factors, the related environmental parameters are shown in Figure 6.The simulation time starts at 12:00 p.m., and lasts 360 minutes.

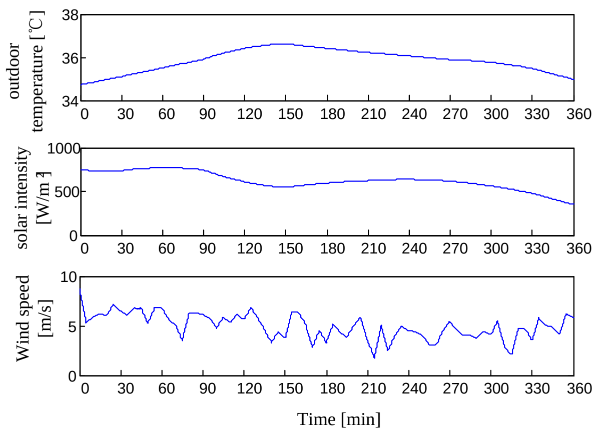


Figure 6. Environment parameters for AC loads

Results

The simulation results of AC cluster participating in real-time dispatching is shown in Figure 7. The green curve is the reference power of AC cluster without DR, the red curve is the target power of AC cluster when AC participating in DR, the blue curve is the actual power of AC cluster in DRTCoS system. When the control instruction or target power is higher than the reference power, AC cluster need to increase load power consumption, leading to indoor temperature reduction, otherwise AC cluster should reduce load power consumption, which results in increase of indoor temperature. AC cluster can respond to real-time scheduling command quickly and accurately.

The changes of normalized indoor temperature when AC cluster takes part in DR are also given in Figure 7, and the relationship between indoor temperature change and AC power adjustment is easy to see. For example, between 90 and 120 minutes, the load power consumption of AC cluster declines, leading to the increase of indoor temperature, what's more, the indoor temperature is always keep within the scope of the customers allowance, guaranteeing the electricity satisfaction levels and comfort levels of customers.

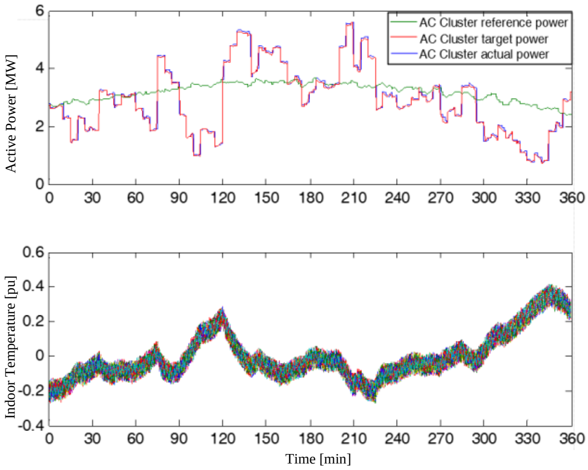


Figure 7. Demand response with AC cluster

CONCLUSION

As an enabling technology, smart grid can transform a large number of reactive load of the demand side to flexible resources with rapid response ability. Dynamic simulation ability for fast DR resources is of great significance for the research on the future smart grid source - grid - load interactive operation control. It's a huge challenge to the real-time simulation with DR resources, because of the characteristics of mass, diversity and responsiveness.

With the idea of multi-rate simulation, this paper proposes an integrated large-scale DR resources of smart grid digital real-time co-simulation method. The chief value of this method is to take full advantage of low-cost general computer to extend the modelling and simulation ability of large-scale DR resources for existing DRTS system, which can constitute smart grid cyber-physical system hybrid simulation platform with communication and control devices. With excellent scalability, the proposed co-simulation architecture can be adopted to the modern mainstream DRTS system.

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