Multi-SGI interconnected real-time HIL simulation of Yu’E MMC-HVDC project

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Abstract. With the interconnection of regional grid and wide application of HVDC and FACTS in power grid, the scale of grid is increasing rapidly, and this makes the power system simulation techniques face new challenges. In this paper, based on decoupling algorithm and high speed optical fiber communication, the interconnection between multi-SGI(multiple SGI supercomputers) is proposed to implement HYPERSIM co-simulation. The HIL test of Yu’E MMC-HVDC project is implemented using the HYPERSIM co-simulation platform, the test results verify the real-time simulation capability of the proposed scheme.

1. Introduction
With the expansion of modern power grid, and wide application of power electronic equipment such as MMC-HVDC, this makes the dynamic characteristics of power grid more complicated. As an effective tool, the SGI based HYPERSIM electromagnetic transient real-time simulation platform has been used effectively in large-scale power system[1-2], however, due to the limited simulation resources, the simulation capability of a single SGI supercomputer is gradually difficult to realize the real-time and accurate simulation for the ever-expanding power grid. In order to solve the problem, electromagnetic and electromechanical transient hybrid simulation has been proposed in some papers to simulate large-scale power grid, but the electromechanical transient simulation is less accurate than electromagnetic transient simulation, although electromechanical transient simulation needs less computation resources[3-5]. In this paper, an interface model is developed, and based on this interface model, two SGI supercomputers can be interconnected to implement HYPERSIM real-time co-simulation.

2. Multi-SGI based HYPERSIM real-time simulation platform
HYPERSIM co-simulation platform composed of multiple SGI supercomputers is based on the same hardware equipment and software architecture, which is very suitable to form a co-simulation platform as concerns about communication and synchronization.

2.1. Scheme of HYPERSIM Co-simulation
SGI based HYPERSIM real-time simulation platform is composed of CPU and FPGA expansion boards. CPU is the main computation unit, which can complete the calculation of large-scale wind farm, LCC-HVDC, MMC-HVDC, large-scale power grid model and so on, FPGA has enormous...
parallel computation units with very fast clock periods (i.e. 5ns or 10ns), therefore, FPGA is ideal for high-precision model calculation, high speed IO and optical fiber communication.

The hardware configuration of co-simulation is shown in figure 1, high-speed PCIe bus is used for real-time communication between CPU and FPGA. The real-time simulation data interaction among SGIs is implemented by Aurora optical fiber communication protocol. Synchronisation can be also managed by the Aurora communication protocol, the end of frame (EOF) of Aurora for the data interaction can be used as the event to trigger the start of the next simulation step.

![Figure 1. Principle of multi-SGI based HYPERSIM co-simulation.](image)

2.2. Decoupling principle of Co-simulation

There are two main decoupling principles of co-simulation, one of them takes advantage of the time delay characteristics of the transmission line as shown in figure 2, which is the Bergeron equivalent circuit of the transmission line, a transmission line can be split into two independent current injection two-port networks[6], the other one uses the equivalent model of inductance $L$ of the circuit to decouple as shown in figure 3, in which $T_s$ is the simulation time-step, and $K$ and $R$ are the values obtained through the equivalence of the inductance $L$.

![Figure 2. Bergeron equivalent circuit for lossless transmission lines.](image)

![Figure 3. Equivalent model of inductance.](image)
In order to interconnect HYPERSIM simulation models running respectively on different SGI supercomputers, an inductance $L$ is divided into two equal parts and run respectively in different SGI, the equivalent model of decoupling inductance in co-simulation is shown in figure 4, in which the inductance $L$ is evenly divided into two parts, so the values of $K$ and $R$ are half of the previous values, where $K_1=K_2=-L/T_s$ and $R_1=R_2=L/T_s$.

![Figure 4. Equivalent model of inductance in Co-simulation.](image)

3. Application of HYPERSIM Co-simulation in MMC-HVDC

In order to verify the simulation capability of HYPERSIM co-simulation, Yu’E MMC-HVDC project is selected as the object of simulation research, and the corresponding real-time simulation model is developed, HIL(Hardware-in-the-loop) test is implemented by connecting the practical control and protection equipment into the Yu’E MMC-HVDC model.

3.1. Yu’E MMC-HVDC project

In order to send the abundant hydropower resources of Sichuan Province and Chongqing City to the central China power grid, State Grid Corporation of China planned the Yu’E MMC-HVDC project. Yu’E MMC-HVDC project is composed of two power transmission channels including Southern Channel and Northern Channel, each channel is composed of two parallel back-to-back MMC-HVDC units, the rated power capacity of each unit is 1250MVA, and the rated DC voltage is $\pm 420kV$[7-9].

3.2. Southern channel control and protection system of Yu’E MMC-HVDC project

Due to the control and protection strategy and main circuit are almost the same between Southern Channel and Northern Channel, Southern Channel is selected as the research object in this paper. The main circuit of Southern Channel is shown in figure 5 as below, as seen from the figure, Southern Channel is divided into two units including Unit1 and Unit2.

![Figure 5. Main circuit of Yu’E MMC-HVDC southern channel.](image)

Main circuit parameters are shown in Table 1 as below:

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Table 1. Main circuit parameters.

| Parameters                                      | Value                                      |
|------------------------------------------------|--------------------------------------------|
| Grid side rated operation voltage              | 525kV                                      |
| Rated DC voltage                               | ±420kV                                     |
| Rated power capacity of each unit              | 1250MVA                                    |
| Number of Submodules of each Arm               | 540(including 40 redundant submodules)     |
| Arm inductance                                 | 140mH                                      |
| Submodule capacitor                            | 11mF                                       |
| interconnection transformer                    | Y0/YN/△, 525/437.23/66kV                  |

Southern Channel control and protection system is shown in figure 6, as can be seen from the figure, the control and protection system is composed of three subsystems including SCC(System Control Center), PCP(Pole Control and Protection), VBC(Valve Base Control).

SCC is mainly responsible for the setup of MMC-HVDC operation mode and monitoring the operation status of MMC converter station. According to different operation mode, SCC sends PCP the corresponding control instruction such as active and reactive power reference values and dc voltage reference value, at the same time, SCC also acquires and displays the measurements of the main circuit, such as grid frequency, voltage, current and power.

The PCP is divided into two parts, namely Unit1 PCP and Unit2 PCP, respectively corresponding to the PCP of Unit1 and Unit2 of Southern Channel. After PCP receives the control instruction from SCC, it executes the corresponding control algorithm to generate 6 reference waves, and sends the 6 reference waves to VBC through the optical fiber communication protocol IEC60044-8. In addition, PCP is also responsible for detecting faults of each unit, and sending alarm signals or directly isolating and removing the faults.

Figure 6. Scheme of control and protection system.
The VBC is divided into four parts, corresponding to the four MMC converters in Southern Channel. The main functions of VBC include circulating current suppression, capacitor voltage balance of submodules, generation of submodules switch instructions, and monitoring the operation status of MMC converter.

3.3. Southern channel HIL test bench of Yu’E MMC-HVDC project

Considering the main circuit of the Southern Channel and the external IO interface requirements of the control and protection system, the HYPERSIM real-time co-simulation platform based on the multi-SGI interconnection is designed and corresponding HIL test bench is established, as shown in figure 7.

As can be seen from the figure, the HIL test bench includes IO modules which are used as IO connection with PCP system, the IO modules can be either digital-to-analog converters (DAC) to send the measured voltages and currents to the actual PCP under test, or optically isolated digital modules to receive circuit breaker commands and send back the circuit breaker positions. Due to there are large amount of IO signals, the IO expansion box is adopted here to extend the IO interfaces. OP7020 is a simulator based on Xilinx Virtex-7TM FPGA. Taking advantage of the parallel computation characteristics of FPGA, OP7020 is particularly optimized for real-time simulation of 6000 MMC Sub-modules under the simulation speed of sub-microsecond time-step. The HIL test bench includes 4 OP7020, which are respectively used for real-time simulation calculation of 4 MMC converters in Southern Channel of Yu’E MMC-HVDC project. In addition, OP7020 is integrated with the Aurora high-speed serial communication protocol to receive submodules switch instructions from the VBC to the MMC converter and feedback the status of the MMC converter to VBC. The Dolphin Switch is used for connecting the simulators such as SGI, OP7020 and IO expansion box to exchange simulation data between them via PCI Express protocol.

The power transmission networks of Hubei grid and Chongqing grid both are complicated, including large scale 220kV substations, 500kV substations and transmission lines. To balance the computation load between multiple SGI supercomputers, the Hubei grid is simulated in one SGI, the Chongqing grid and Southern Channel of Yu’E MMC-HVDC is simulated in another SGI, and the two parts are decoupled using a 500kV transmission line, the two ends of the transmission line are simulated in 2 SGIs respectively, and interfaced by optical fiber communication between 2 SGIs.

![Figure 7. Scheme of HIL test bench.](image)

4. Performance test

Based on the designed HIL test bench, performance test of the Southern Channel control and protection system is implemented, hundreds of scenarios have been tested. Due to the limitation by the length of this paper, only a few typical test scenarios are present as below.
4.1. Power control test
Power control test is used for testing the power adjustment performance of control and protection system during steady state operation mode, the Hubei side active and reactive power reference value of Unit2 are set at 1250MW and 518MVAr respectively. Test results are shown in figure 8 as below, in the figure, Unit2 can be controlled at the power point with the active power of 1250MW and the reactive power of 518MVAr stably. The power control performance is validated.

![Figure 8. Simulation results of HVDC.](image)

4.2. Grid side single phase to ground fault test
In this test, the initial active power is at 1250MW, and initial reactive power of Chongqing and Hubei side are both at 400MVAr, a single phase to ground fault is applied at the Chongqing grid side of Unit2, and cleared after 1s. In figure 9, the system responses to the fault are presented, as can be observed from the figure, when the fault happens, fault ride through control is triggered, and the converter side three phase current still maintains balanced while there is no overcurrent appeared, after the fault is cleared, Unit2 resumes to initial operation status. The test results prove that the control and protection system can work well under the fault.

4.3. Pole-to-ground DC fault
In this test, the initial active and reactive power of Chongqing side is at 1250MW and 365MVAr respectively. A positive pole-to-ground DC fault is applied at the DC side of Unit2, and cleared after 1s.

The system responses to the fault are presented in figure 10, as observed from the figure, after the fault happens, due to the fault changes the grounding mode of the main circuit, the DC voltage of positive pole to ground drops to nearly zero while the DC voltage of negative pole to ground drops to nearly -840kV. Then the control and protection system block MMC converters, and open AC breakers. The test results prove that the control and protection system can correctly detect faults and perform appropriate protection actions under the fault.
Figure 9. Grid side single phase to ground fault test.

Figure 10. DC positive pole to ground fault test.
5. Conclusions
In this paper, transmission line and inductor are selected as decoupling elements to partition large power grid, and a HYPERSIM real-time co-simulation platform is designed by interconnecting multiple SGIs with optical fiber communication. Based on the platform, a HIL test bench for the Southern Channel control and protection system of Yu’E project is established, the HIL test verifies the performance of the control and protection system, and also validates the real-time simulation capability of large power grid by the designed HYPERSIM co-simulation platform.

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