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# The hybrid simulation system of hydropower generation units in islanding AC grid and its applications

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**Abstract.** It is a trend for the large hydropower bases to transport the electricity to consuming center with High Voltage Direct Current (HVDC) transmission lines. The fault of HVDC has great significance impact on hydropower units in islanding sending AC grid. In this paper, a hybrid simulation system is established to analyze the dynamic characteristic of hydropower units in islanding system. The simulation system is based on Real Time Digital Simulator (RTDS) and Digital Signal Processor (DSP). The simulation of electromagnetic transient process in the generator, the load, the network and HVDC is completed by RTDS. The Hydroturbine Real Time Simulator (HRTS) based on DSP completes the simulation of hydraulic-mechanical-electrical transient process in hydroturbine, division system and governing system. The real time data communication between RTDS, HRTS and external equipment ensures the real time calculation of simulation. The simulation results show high coincidence with field data. The hybrid simulation system is an effective approach for the research of islanding system at sending terminal with HVDC.

## 1 Introduction

The world is urging for the renewable and green energy to reduce the pollution caused by fossil energy. The renewable energy has experienced great development in recent years. As the most widely used and mature renewable energy, the hydropower has occupied a large proportion in the newly developed renewable energy [1, 2]. In China, the new hydropower plants, which is often of great single-machine capacity, are often constructed in the underdeveloped western region far from the load center [3]. The HVDC is employed as the long-range bulk power transmission solution by the new large hydroelectricity bases in recent years [4].

The application of HVDC often results in the weak connection between the power stations and the main power gird. These stations comprise an islanding AC grid with little load at sending terminal. The islanding operation mode receives much interest in recent years and has been widely used in the distributed renewable energy generation [5-7]. It improves the stability significantly by assembling the distributed generation units in a microgrid [5]. The composition of the islanding system is quite different from that of traditional power grid. The stability and control strategy of islanding system need to be studied in depth [6]. Robert J. Best et al. studied the techniques of multiple-set control [8]. Guillermo Martínez-Lucas et al have analysed the frequency control strategy in isolated system composed of hydropower and wind power [9]. In ref. [10], the stability of wind power in small isolated system was discussed. Urban Rudez et al. studied the under frequency load shedding scheme for islanded system with renewable generation [11]. In previous research, the islanding system is often composed of a large quantity of distributed generation units with small single-machine capacity, such as wind power, solar power and small hydro power [6, 7]. However, with the construction of large hydropower stations in Chinese western area and the division of bulk power grid into several asynchronous interconnected grids with HVDC transmission, an increasing number of hydropower stations have adopted the islanding operation mode. Then a new islanding system composed of one or several large hydropower stations appears. Different from the islanding system composed of distributed generation, the new islanding system consists of one or several large hydropower stations with large single-machine capacity. The occupation of each unit in the system is relatively big. With less local load in the islanding system, most of the power should be transport to bulk power grid through HVDC transmission lines. Under this condition, the fault of HVDC has great negative influence on the hydropower units in such an islanding system. Besides, for the existence of water hammer, the transient stability of hydropower units is relatively poor [12]. It is necessary to study the control strategy of the hydropower units in such emerging islanding systems. Chao Yang et al. has studied the integration of variable speed hydropower generation and VSC HVDC [13], while they failed to consider the governing system. GT. Zhang et al. has studied the supplementary control strategy of hydroturbine governor for islanding AC grid at sending terminal [14].

Various tests are required on the control equipment for the research of control strategy of islanding system. The tests in the actual power grid are not available so that the simulation has become the first choice for the research. For this purpose, this paper presented the structure of hybrid simulation system based on RTDS(Real Time Digital Simulator) and HRTS(Hydroturbine Real Time Simulator). Finally, two simulation cases are given to illustrate the accuracy and feasibility of the system.

## 2 The structure of the hybrid simulation system

The hybrid simulation system is composed of HRTS, RTDS and the monitoring computer, as shown in Fig. 1. HRTS completes the simulation calculation of the hydroturbine, the division system, the governor and the servo system. The RTDS completes the calculation of generator, excitation system, load and network as well as HVDC. The HRTS and RTDS can exchange data real time to complete the simulation together.

There are two simulation modes of the hybrid simulation system. Mode 1 is the full system simulation mode; Mode 2 is the partial system simulation mode.

In mode 1, the full system is simulated. The simulation calculation process is divided into four steps:

1) In HRTS, the output torque $m_t$ and the flow $Q$ of hydroturbine are calculated by the hydroturbine and division system equations based on the initial value of guide vane opening y, water head h and rotor speed x;

2) RTDS receives the $m_t$ from HRTS and calculates the present speed x by the equations of generator, excitation system, load and network;

3) HRTS receives the speed signal x, the terminal circuit breaker signal, island operation signal and DC outage signal from RTDS. The guide vane opening y is calculated by the governor and servo system model;

4) According to the new parameters, the $m_t$ and $Q$ at current moment are calculated by the hydroturbine model and division system model. The calculation next is the repetition of the step 2, 3 and 4 until the final results are obtained.

Mode 1 allows the inline modification of the adjusting parameters and control logic of control system. Users can analyze various control strategy in this mode.

In mode 2, the simulation of governor or the control part of governor is realized by the actual equipment instead of the mathematical models. The actual governor obtains the speed signal x from RTDS and then calculates the opening gate y. HRTS is only responsible for the simulation calculation of the hydroturbine and division system or the hydroturbine, division system and servo system. The simulation calculation process of mode 2 is different from that of mode 1 in step 3: The real governor measures the frequency of the AC voltage signal (amplified by power amplifier) of generator from RTDS and then calculates the guide vane opening y. HRTS obtains the guide vane opening y from the governor. Other computational steps are the same with mode 1. By involving the actual equipment in the calculation progress, the mode 2 is available for the check of the actual equipment.

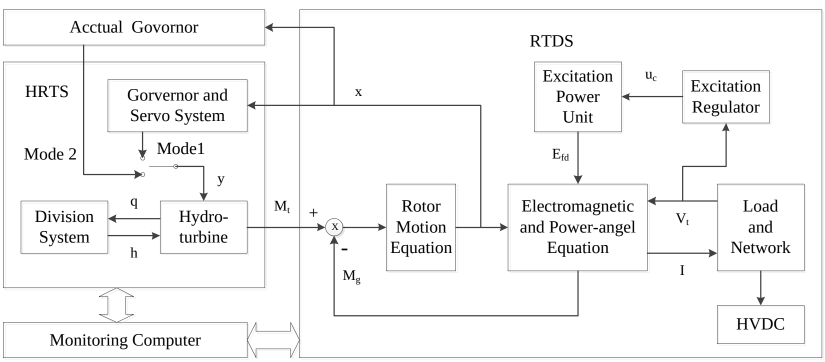



**Fig. 1.** Real-time simulation system of hydro-power unit.

## 2.1 The HRTS based on DSP

HRTS is composed of several modules based on DSP. One DSP module can complete the simulation of four units. The number of DSP modules is determined by the need of simulation. The structure of the module is shown in Figure 2. With the requirement for high-speed real time simulation in HRTS (1ms step size), the TMS320F28335 chip with floating processor unit is selected. HRTS adopts the forward and backward system structure without operation system in calculation programming to reduce the occupation of CPU resources. The C Language is used in programming of mathematical model. The calculation method adopts the floating model based on floating processor unit to reduce calculation time consumption and improve calculation accuracy. The test results illustrated that the ADC conversion time is 0.16μs, the calculation time of one step is less than 200μs, and DA output time is 10μs. According to the analysis and test, the real-time performance of HRTS can fulfil the request that the time consumed in one step calculation is less than 1ms.

The HRTS enables both analog communication and digital communication. As for the analog communication, the 16 channel 12 bits A/D converter in DSP is used for the acquisition of the analog quantity from RTDS and external equipment. A DAC7724 chip is inserted in HRTS to achieve D/A output to send results to RTDS. To achieve digital communication, two w5100 Ethernet chips are integrated in HRTS. One is for the communication with backward monitoring computer. The other is used for digital communication with RTDS.

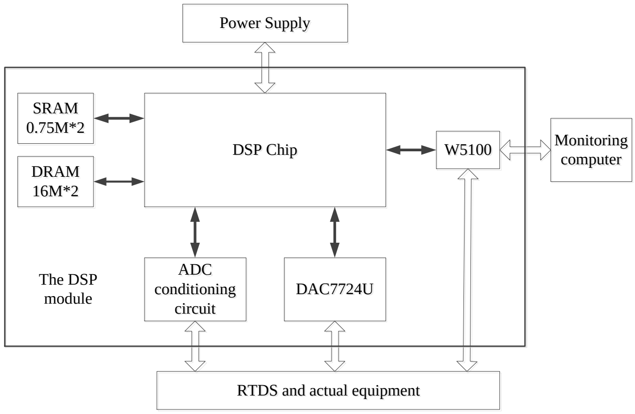



**Fig. 2.** The Structure of DSP module of HRTS.

### 2.2 RTDS simulation system

A set of RTDS device in the hybrid simulation system includes three basic cards: Processor Card (TPC), Inter-Rack Communication Card (IRC) and Workstation Interface Card (WIF). TPC is the core component which is responsible for the simulation mathematical calculation in RTDS. In each TPC, two independent DSP chips and the parallel processing architecture are integrated to accomplish the high-speed simulation calculation. To realize the analogue and digital communication, RTDS is equipped with GTAI, GTAO, GTDI and GTDO cards. GTAI and GTAO cards achieve 16-channel analogue outputs and 4-channel inputs for the communication with HRTS and the actual governor. GTDI and GTDO cards can achieve 32bits high-precision digital input/output for the grid-connection control of hydropower units and the HVDC blocking control.

### 2.3 Real time monitoring system

To supervise the calculation process of the simulation system, the real time monitoring system for HRTS is developed by the test system development tool LabWindows/CVI. The monitor system enables the real time supervision of simulation process. The system can realize the real time curve display, recording and playback for all parameters.

The monitoring system also provides the good human-machine interaction. Users can modify the parameters online via the monitoring system and the commands from users are sent to HRTS by the monitoring computer. It enables users to simulate different operation condition with various disturbance signals. By modifying the regulating parameters, users can analyse the impact of regulating parameters on governing system. By changing condition parameters, the real time simulation of overall working condition is realized.

## 3 Data interaction between DSP, RTDS and external equipment

The smooth data interaction between HRTS, RTDS and external equipment is the guarantee for the implementation of the hybrid system. There are three data transmission paths in the hybrid simulation system: 1) the data communication between HRTS and RTDS. The transmitted data are the hydroturbine torque $m_t$ and unit speed $x$; 2) the data communication between HRTS and monitoring computer. The transmitted data are the parameters of hydropower unit; 3) the data communication between the HRTS, RTDS and the actual control equipment. The transmitted data are the guide vane opening $y$, unit speed $x$, the terminal voltage and so on.

### 3.1 Data interaction between HRTS and RTDS

Two communication mechanisms are available for data exchange between HRTS and RTDS. One is the analog data communication. The other is the digital data communication.

The analog data communication is based on A/D and D/A conversion. In HRTS, a high-precision DAC chip DAC7724 is integrated in the DSP main board to complete the A/D conversion of the output signals. To ensure the real time performance of simulation, the input signal is sent to DSP directly. The A/D conversion of input signals is completed by the A/D converter in DSP. In RTDS, two GTAI cards and two GTAO cards are extended for the analog communication with HRTS. HRTS has built 16-channel analog signal input to obtain signals from RTDS and 4-channel analog signal output to send signals to RTDS.

Digital data communication is based on SV message protocol. SV protocol is a real time communication protocol involved in IEC61850 Standards. It is specially designed for the analog sample data communication. In SV message, a data segment is used to describe the analog sample data. The data segment is divided to 8 channels, which are used to transmit the sampled values of unit speed and hydroturbine torque of four simulated units in the hybrid system. The SV protocol is based on the OSI model. Only four layers are used, which are the application layer, representation layer, data link layer and physical layer. Referring to the hardware, the w5100 chip is integrated in HRTS to achieve the digital data communication. The w5100 chip supports the Ethernet communication programmed in physical layer. RTDS is equipped with the GTDI and GTDO cards to achieve the high-precision digital communication.

### 3.2 Data interaction between HRTS and monitoring system

The digital data communication based on TCP/IP protocol is adopted for the communication between HRTS and monitoring computer. HRTS transmits the data to monitoring computer by the w5100 chip. The w5100 is with TCP/IP protocol inherent. The transmission speed can reach 100Mbit/s. The internet connection without operation system is used in the communication between w5100 and monitoring computer to ensure the high-speed communication. The direct bus mode, which means the w5100 is connected with DSP via the data bus and address bus, is adopted to reduce consumption of communication on CPU resources. The transmitted data includes the calculation results of the condition parameters. The monitoring computer is also able to send the modified parameter to HRTS in same way.

### 3.3 Data interaction between the hybrid simulation system and the external governor

In simulation mode 2, the actual governor participates the calculation of the system. The analog data communication mechanism is adopted because it is used in the real hydropower unit operation. The data interaction occurs in two places: 1) the governor receives the analog voltage signal from RTDS. The governor samples and converts the analog signal of generator terminal voltage from RTDS and obtains the frequency. 2) HRTS receives the signal from the governor. The governor calculates the $y_c$ and sends it to the servo system. HRTS obtains the $y_c$ from the governor or the y from sensors of guide vane. The analog signal is converted by the ADC on DSP chip and used for calculation.

### 3.4 The real time performance of data interaction

The stable and smooth data communication determines the steady and long-time real time operation of the hybrid simulation system. The complex interaction sequence is not necessary to achieve the real time calculation of the hybrid system. The hybrid system can realize the real time communication with these reasons:

The step size in both HRTS and RTDS can reach 50μs. The step size is small enough for the high-precision simulation calculation.

The transient calculation in RTDS is based on the conservation principle of flux linkage. At the moment of the change of operation condition, the transient force is proportional to the flux linkage and cannot change abruptly. In the transient process, the speed signal $x$ from RTDS to HRTS is the integration of the $\Delta m_t$. When $m_t$ is unchanged, the deviation of $x$ is tiny and can be neglected.

The step size of the governor is 20ms, which is much larger than that of RTDS. So, the deviation of $x$ has little influence on $y$. What's more, the $m_t$ is calculated by the $h$, the $y$ and the $x$. The influence of the deviation of $x$ on $m_t$ is reduced further.

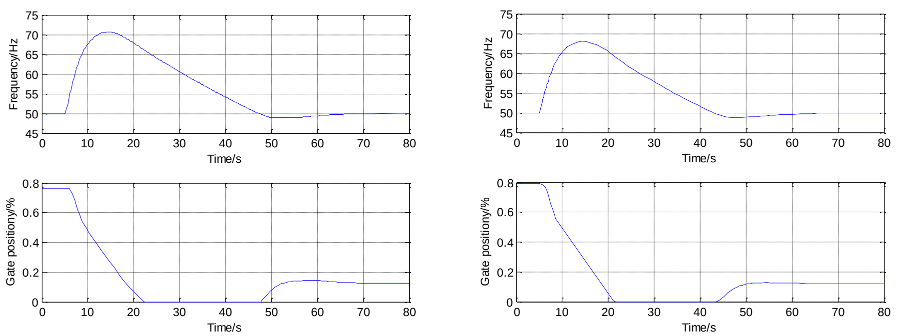
For these reasons, the real time simulation is achieved by connect HRTS with RTDS directly.

## 4 Engineering applications

The real time hybrid simulation system proposed in this paper has already been applied and played a role in the Chusui HVDC projects. The hybrid system is effective in the simulation tests and the check of the real equipment. Two applications are given below as the cases. In each case, the data of simulation mode 1, simulation mode 2 and field test are given to illustrate the effectiveness of the simulation system.

### 4.1 Application case 1

The application case 1 is the 100% load rejection test in JAQ plant. The behaviour of units after turning off the generator-end circuit breaker is simulated by the hybrid simulation system with both simulation mode. The parameters of the initial condition are near to rated values. The results of simulation and field test are shown in Table 1 and Fig. 4. In Fig. 3, the subgraph a, b, c are the results of field test, simulation mode 1 and simulation mode 2. The results of simulation show high coincidence with field data.




(a) (b)

**Fig. 3.** The results of simulation mode 2 and field test in 100% load rejection test.

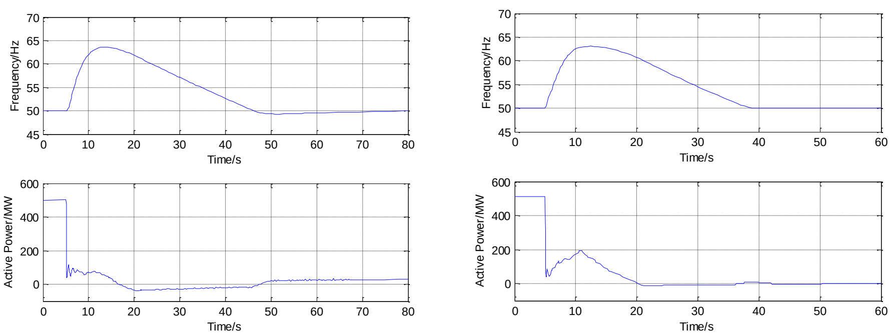
(a) Field test, (b) Simulation mode 2

**Table 1.** The results of simulation mode 1, 2 and field data in 100% load rejection test.

| Test type | | mode 1 | mode 2 | Field Test |
|---|---|---|---|---|
| Initial Opening/% | | 77.80 | 79.10 | 76.01 |
| Initial Load/MW | | 576 | 583 | 588 |
| Maximum Frequency /Hz | | 69.15 | 68.1 | 70.57 |
| Minimum Frequency /Hz | | 49.07 | 48.7 | 48 |
| Occurrence /s | Maximum Frequency | 7.9 | 8 | 7.5 |
| | Minimum Frequency | 46 | 42.5 | 45.5 |
| Stable Opening /% | | 12 | 12 | 12 |

## 4.2 Application case 2

The application case 2 is the bipolar block test in JAQ plant. In this test, the behaviour of the hydropower unit when bipolar block happens is simulated. JAQ plant is at sending terminal of Chusui HVDC transmission. In JAQ plant, the six units are the same. The water head is the rated value. The initial load is 510MW. The simulation results and field data of Unit 1# are shown in Table 2 and Fig. 4. It can be observed that the peak value, the rising time and stable value of frequency in simulation test is in essentially agreement with field data. The recovery of frequency in simulation is faster than the field test.




(a) (b)

**Fig. 4.** The results of simulation mode 2 and field test in bipolar block test.

(a) Field test, (b) Simulation mode 2.

**Table 2.** The results of simulation mode 1, 2 and field data in bipolar block test.

| Test type | | mode 1 | mode 2 | Field Test |
|---|---|---|---|---|
| Initial Load/MW | | 513 | 513 | 510 |
| Maximum Frequency /Hz | | 62.90 | 62.6 | 63.64 |
| Minimum Frequency /Hz | | 49.94 | 49.8 | 46.32 |
| Occurrence /s | Maximum Frequency | 7.70 | 7.7 | 8.50 |
| | Minimum Frequency | 38.04 | 35.7 | 45 |
| | Positive Power | 16.43 | 16 | 17.11 |
| | Negative Power | 35.65 | 35 | 41.35 |

## 4.3 Discussion

It can be observed from the application cases above that the hybrid system can simulate the islanding system in high precision. The results of simulation mode 1, simulation mode 2 and field test show high coincidence. It demonstrates that the mathematical model of the system is accurate enough to describe the characteristic of the islanding system. The real time performance of the hybrid simulation system has been achieved to ensure the real time calculation. The system is proved to be effective. Various tests which are unable to be conducted in the power grid can be simulated by the hybrid simulation system.

## 5 Conclusions

A hybrid simulation system of hydropower units in islanding AC system at sending terminal with HVDC is built based on RTDS and HRTS. RTDS is used for the calculation of electromagnetic transient process. HRTS simulates the hydraulic-mechanical-electro dynamic process of hydropower units. The system has achieved the precise simulation of nonlinear components including the hydroturbine, which makes up the deficiency that RTDS cannot carry out the nonlinear calculation. The system enables the precise analysis of the transient and dynamic process of sending terminal system with HVDC.

The system can complete the simulation of overall operation conditions with various control strategies, including the faulty conditions. It provides a new approach to study the control strategy and operational safeguards of hydropower units in the island system, especially the coping strategy for HVDC faults. The hybrid simulation system has been used in the Chusui HVDC project and its effectiveness has been validated.

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