Hardware-in-loop test platform design for AVC sub-station of the new energy station based on RT-LAB

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Abstract. In order to ensure the safe and stable operation of the large power grid with high proportion of renewable energy access, the automatic voltage control (AVC) system of the new energy power station is very important. The control strategy of the AVC and the response characteristics of the voltage and reactive power regulating equipment will affect the AVC regulation effect directly. However, the pure digital simulation software cannot simulate its actual response characteristic. This paper established a hardware in loop (HIL) testing platform based on RT-LAB real-time simulation system. The real AVC controller and the real static var generator (SVG) controller hardware are connected to RT-LAB testing platform via I/O physical interface and MODBUS communication, and the HIL coordinated simulation testing scheme is studied based on FPGA of RT-LAB. With established testing platform, the voltage regulating characteristic and reactive power replacement capacity of AVC control strategy is verified.

1. Introduction
With the continuous development of power system, the scale of power grid is expanding day by day, and the stability of voltage is important to the safety, quality and economic operation of power system. In order to adapt to the complexity of power grid, automatic voltage control system (AVC) came into being. AVC refers to the online calculation of control strategy according to the real-time operation of power grid and the automatic closed-loop control of reactive power and voltage regulation equipment, with computer systems, communication networks and adjustable equipment, in order to achieve a reasonable distribution of reactive power and voltage [1]. AVC system includes the master-station and the sub-station, and actually, the sub-station uses the supervisory control and data acquisition (SCADA) system to monitor the real-time operation status of power grid, and upload the monitored telemetry as well as remote signaling data to the AVC master-station for optimization decision. Then, the master-station sends the target voltage command or target reactive power command to the sub-station. Finally, with receiving the command, the AVC sub-station coordinates the voltage and reactive power regulation equipment through the control strategy, and sends the command through the remote control and remote regulation function of the SCADA system to realize automatic, closed-loop and optimal control of voltage.

In recent years, the proportion of new energy access to the power grid has increased explosively, and the security and stability problems of power grid are increasing gradually. New energy has the
characteristics of randomness and volatility, and thus the grid-connection of the large-scale wind power station and photovoltaic power station will have a significant impact on the power flow of power grid. In order to ensure the safe and stable operation of the large power grid with a high proportion of renewable energy, the AVC system of new energy power station is very important. The AVC sub-station of the new energy station receives the target command and controls the voltage adjustment equipment such as the wind turbine, the photovoltaic inverter, the static var compensator (SVC), the static var generator (SVG), the on-load voltage regulating tap of the main transformer and so on, to maintain the voltage stability of the parallel grid and ensure the safe operation of power system.

The control strategy of the AVC sub-station and the response characteristics of the voltage and reactive power regulating equipment in the new energy station will affect the AVC regulation effect directly. However, the pure digital simulation software cannot simulate the actual response characteristics of the various voltage and reactive power regulating devices in the AVC system control process. There are certain errors in optimizing and verifying the control strategy of the AVC sub-station. While, the hardware in loop (HIL) simulation test makes up this disadvantage, which can effectively verify the effectiveness of the control strategy and the dynamic response performance of each device under a more real environment. Reference [2] built the HIL simulation design platform of the wind turbine converter based on RT-LAB, and the algorithm of the converter is developed and verified. Reference [3] presented a semi-physical simulation experiment of photovoltaic system maximum power point tracking based on semi-physical real-time simulation technology. Reference [4] presented a testing system for power converters control units and a HIL test is designed for assessing control unit performances. Reference [5] designed the HIL simulation testing for the controller of three-level photovoltaic grid-connected inverter by RT-LAB. But there is few literature building the HIL simulation platform of AVC controller.

This paper establishes a HIL testing platform for AVC sub-station of the new energy station based on RT-LAB, to simulate and verify the voltage and reactive regulation ability of AVC sub-station control strategy. The real AVC controller and the real SVG controller hardware are connected to RT-LAB testing platform via I/O physical interface and MODBUS communication, and the HIL coordinated simulation testing schemes for the power grid, photovoltaic generating system, SVG valve body are studied based on FPGA of RT-LAB.

2. AVC of new energy station

The AVC sub-station of new energy station coordinates and controls the reactive power regulating equipment with different characteristics, to ensure that the voltage at the parallel network point of the station can follow the voltage of high voltage side bus regulation command from the AVC master-station in provincial dispatching. The specific implementation process includes:

- (1) AVC sub-station monitors the operation mode of each generating unit and reactive power compensation device in the station, evaluates the reactive power reserve of the station, calculates the dynamic reactive power regulation capacity of the station and sends it to the AVC master-station for grid dispatching.
- (2) The AVC sub-station receives the total reactive power command or receives the target bus voltage command at the high voltage side from the AVC master-station, and calculates the reactive power regulation value of the station through the real-time operation status monitoring information.
- (3) AVC sub-station calculates the reactive power real-time distribution of each reactive power source in the station according to its control strategy, and continuously orders the reactive power source during every regulation cycle until the voltage or reactive power of the parallel node meets the command from the master-station.

When adjusting the reactive power output of every reactive power sources in the station in accordance with the instructions of the master-station, the wind turbine and photovoltaic inverter provide the basic reactive power support preferentially and the SVC/SVG is responsible for the fine...
tuning. However, SVC / SVG equipment adjusts concurrently for their rapid dynamic response, and after the reactive power regulation completed according to the established strategy, the reactive power of SVC / SVG equipment shall be replaced by wind turbine and photovoltaic inverter, to make SVC / SVG equipment have dynamic reactive power reserve.

3. Construction of RT-LAB semi-physical simulation platform

3.1. Test system overview
This paper simulates a centralized grid-connected photovoltaic field station through simulation modeling. The reactive devices of the station include photovoltaic inverters and SVG. The hardware part of RT-LAB semi-physical real-time simulation system consists of SVG controller, AVC controller, communication manager of AVC controller, host computer of AVC controller, RT-LAB simulation host and simulation targets. The software part includes Matlab-simulink, RT-LAB main program, ARTEMIS toolbox and RT-Events toolbox, etc. The structure of the test system is shown in Figure 1. In our simulation testing platform, the real AVC controller and the real SVG controller hardware are connected to RT-LAB testing platform via I/O physical interface and MODBUS communication. The photovoltaic array model and the grid model are constructed using Matlab-simulink.

3.2. Simulation modeling
The HIL test simulation model for AVC sub-station of the new energy station includes three subsystems. The subsystem SM_system mainly simulates the main circuit topology, SVG topology, photovoltaic power station and AVC communication module. The subsystem SS_control mainly simulates the I/O port between the SVG controller and RT-LAB. The subsystem SC_console mainly displays the waveform, including the voltage and current of the parallel point, the output of photovoltaic array, the reactive power of the inverters, and the reactive power of SVG. The overall structure of the model is shown in Figure 2.
Figure 2. The overall structure of the simulation model.

The main circuit topology of the system in the subsystem $SM_{\text{system}}$ includes three parts: the main circuit of power grid, the photovoltaic station and the SVG valve body. The main circuit topology mainly simulates the power grid, the main transformer and the load. The photovoltaic station is a digital simulation model based on Matlab-simulink, consisting of battery and inverter and receiving the target reactive power command from AVC. The SVG valve body is a digital model of H-bridge structure, which interacts with the SVG hardware controller through the I/O interface for analog and digital data. The valve body sends the sub-module voltage and grid parameters to the SVG controller, and receives control pulse from the SVG controller, thus realizing the normal operation of the digital valve body.

The AVC controller communicates with the SVG controller through MODBUS-RTU protocol after allocating the front communication manager, reads the SVG reactive power output and its margin in SVG controller, and sends the calculated reactive command to SVG controller. Meanwhile, AVC controller communicates with FPGA of RT-LAB through MODBUS-RTU protocol, reads the telemetry values of active power, reactive power, bus voltage, power factor, frequency, main transformer tap position, active power and reactive power of inverters, and sends the active command and reactive command of inverters to realize voltage and reactive power regulation closed-loop control with connecting SVG controller and AVC controller simultaneously.

4. Examples

4.1. Test content

This article simulates a 50MW photovoltaic field station, which is connected to the grid through a 110 kV bus. Considering the simulation limitation of the calculation scale of the power electronics device model, the photovoltaic power generation equipment of the station is idealized into 3 units. The total reactive power capacity of inverters is $\pm 16.60$ MVar, and the SVG adjustable reactive capacity is $\pm 12.50$ MVar. The tested AVC control strategy includes two modes: the similar margin mode and the similar proportional mode.

- The similar margin mode: the allocation ratio of the upward/downward adjustment amount of SVG and inverter is equal to its current upward/downward adjustable margin ratio.
- The similar proportion mode: the allocation ratio of the upward/downward adjustment amount of SVG and inverter is equal to their configured capacity ratio in the new energy station.

The test includes the verification of reactive power distribution strategy, voltage regulation response time, voltage regulation response accuracy and the reactive power replacement function. The reactive power replacement function refers that the reactive power input by the dynamic reactive power compensation device is replaced by adjusting the reactive power output of the wind turbine and photovoltaic inverter after achieving the target voltage.
4.2. Data analysis

Table 1. AVC reactive power allocation in the similar margin mode.

| Voltage adjustment | Reactive power source | Initial reactive power output (MVar) | Reactive command (MVar) | Increase the reactive power margin (MVar) | Theoretical reactive power margin ratio | Actually adjusting the reactive power ratio |
|-------------------|-----------------------|--------------------------------------|-------------------------|------------------------------------------|----------------------------------------|---------------------------------------------|
| Working condition 1: 111-113KV | SVG                   | 0.57                                 | 1.96                    | 11.93                                    | 1:1.20                                 | 1:1.24                                      |
|                    | Inverters             | 2.21                                 | 3.94                    | 14.37                                    |                                        |                                             |
| Working condition 2: 113-116KV | SVG                   | 3.57                                 | 12.03                   | 0.47                                     | 1:0.84                                 | 1:0.85                                      |
|                    | Inverters             | 9.10                                 | 10.12                   | 6.48                                     |                                        |                                             |

Adopting the similar margin mode, two test conditions are set: (1) Adjust the high-voltage side bus voltage of the power station from the initial value of 111.32 kV to the target value of 113.00 kV (the dead zone is 0.4 kV); (2) Adjust the bus voltage on the high-voltage side of the power station from the initial value of 113.12 kV to the target value of 116.00 kV. The initial output of SVG and inverters, the reactive power command and the upward margin of reactive power are shown in Table 1.

![Figure 3. The voltage and reactive power waveform.](image)

![Figure 4. The reactive power distribution between different inverters.](image)

After calculation, the reactive target command complies with the similar margin ratio. The variation trend of the voltage and the reactive power of inverters and SVG under the working condition 1 (111-113 KV) is shown in Figure 3. The reactive power distribution between different inverters is shown in Figure 4.

The scopeview waveform analysis function of RT-LAB is used to analyze the voltage regulation process and voltage stabilization process under the working condition 1 (111-113 KV). The voltage regulation process is shown in Figure 5. It can be seen that the bus voltage variation at the high voltage...
side between 110.731-112.820 kV, and the response time when the voltage is adjusted to the target value is 16.13 seconds.

The voltage stabilization process under the working condition 1 (111-113 KV) is shown in Figure 6. As can be seen from Figure 6, with setting the target voltage 113KV, the high-voltage bus fluctuates within the range of 112.574-112.943 KV after the bus voltage adjustment completed.

It can be known from Figure 3-4 that there is no unreasonable flow between photovoltaic inverters and SVG. After the voltage was adjusted to the target voltage 113KV under the working condition 1 (111-113 KV), reactive power replacement was started. By setting the SVG replacement reactive dead zone to 1MVar, the SVG reactive power was adjusted from 2.78 MVar to 0.76 MVar, and the sum of reactive power of inverters was adjusted from 3.32 MVar to 5.11 MVar, achieving the reactive power replacement.

When the adjustment strategy of the AVC sub-station is the similar proportion mode, two test conditions are set: (1) Adjust the bus voltage on the high-voltage side of the power station from the initial value of 110.28 kV to the target value of 109.00 kV (adjusting the dead zone to 0.4 kV); (2) Adjust the high-voltage side bus voltage of the power station from the initial value of 109.20 kV to the target value of 107.00 kV. Observing the output of SVG and inverters, we can see that the initial reactive power command and the configured reactive capacity are shown in Table 2. After calculation, the reactive target command complies with the similar proportion mode. It has been verified that under the similar proportional mode, the voltage regulation response time, voltage regulation response accuracy, and reactive power replacement function meet the test requirements.

| Voltage adjustment       | Reactive power source | Initial reactive power output (MVar) | Reactive command (MVar) | Configured reactive capacity (MVar) | Theoretical reactive power margin ratio | Actually adjusting reactive power ratio |
|--------------------------|-----------------------|--------------------------------------|-------------------------|-------------------------------------|----------------------------------------|----------------------------------------|
| Working condition 1: 110-109 kV | SVG                   | 0.46                                 | -0.68                   | ±12.5                               | 1:1.33                                 | 1:1.32                                 |
|                          | Inverters             | 0.40                                 | -0.90                   | ±16.6                               |                                        |                                        |
| Working condition 2: 109-107 kV | SVG                   | -0.68                                | -2.02                   | ±12.5                               | 1:1.33                                 | 1:1.33                                 |
|                          | Inverters             | -0.90                                | -2.68                   | ±16.6                               |                                        |                                        |
5. Conclusion
This paper established a HIL test platform design for AVC sub-station of the new energy station based on RT-LAB, and the reactive power distribution strategy, the voltage control response time, the voltage response accuracy and reactive power replacement function of AVC controller are tested. The experimental results are basically consistent with the field test results, which verifies the effectiveness of the HIL simulation platform.

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