Power in the loop real time simulation platform for renewable energy generation

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Abstract. Nowadays, a large scale of renewable energy sources has been connecting to power system and the real time simulation platform is widely used to carry out research on integration control algorithm, power system stability etc. Compared to traditional pure digital simulation and hardware in the loop simulation, power in the loop simulation has higher accuracy and degree of reliability. In this paper, a power in the loop analog digital hybrid simulation platform has been built and it can be used not only for the single generation unit connecting to grid, but also for multiple new energy generation units connecting to grid. A wind generator inertia control experiment was carried out on the platform. The structure of the inertia control platform was researched and the results verify that the platform is up to need for renewable power in the loop real time simulation.

1. Introduction

Traditional power system simulation mainly include pure digital electro-mechanical transient simulation, pure digital electro-magnetic transient simulation. Currently, the real time simulation, Rapid Control Prototype (RCP) and hardware in the loop (HIL) are widely used [1-4]. Honghao Guo et al develops the wind turbine simulator model based on torque control of brushless dc motor by using RT-LAB [5]. Xiaotian Wu et al sets up the grid side converter model of a wind generator by RT-LAB, and the hardware in the loop simulation has been done with real controller [6]. Daqiang Bi et al researches the dynamic characteristics after the wind generation system connects to grid [7]. Compared to traditional pure digital simulation and hardware in the loop simulation, power in the loop simulation has higher accuracy and degree of reliability, furthermore, it provides new method for the research of integration control, power system stability, the interaction between grid and power supply. Especially now, more renewable energy generation facilities have connected to grid, so lot of power electronic equipment exists in power system, including grid -connected inverter, DC transmission equipment, statcom etc. This phenomenon has proposed new requests for scale, accuracy and flexibility of power in the loop simulation. This paper researches a kind of renewable energy generation power in the loop analog digital hybrid simulation platform, which has the ability of analog-digital hybrid real-time simulation in the case that multiple new energy generation units connect to grid. At last, wind power generator inertia control experiments was carried out on the power in the loop platform [8,9]. With the power in the loop platform, the inertia control strategy can be realized in DSP by c code to control a 10kw wind experimental platform, The grid models is built by simulink and download into the RT-Lab. The whole platform can be used to verify the real...
controller hardware and software and greatly improved the real time simulation precision and confidence level compared to traditional real time simulation [10,11].

2. The setup of renewable energy generation power in the loop simulation platform

This paper has built renewable energy generation analog digital hybrid power in the loop real time simulation platform, as shown in Figure 1. This platform includes four parts, respectively RT-LAB real time simulation system, power amplifier, flexible interface system, renewable energy power generation units, and other equipments.

![Figure 1. Renewable energy generation analog digital hybrid simulation experiment platform.](image)

2.1. RT-LAB real time simulation system

RT-LAB is real time simulator of Canada OPAL-RT Technologies and it is based on Matlab/Simulink. In Simulink environment, the model can be built into C code automatically and download it into the RT-LAB simulator, as is shown in Figure 2.

![Figure 2. RT-LAB real time simulator.](image)

RT-LAB can realize real time simulation mainly because of its distributed parallel computing technology. Simulation model is divided into multiple subsystems and these subsystems are assigned to multiple target simulator or processors, shortening the solving time and improving the calculation accuracy.

2.2. Power amplifier and flexible interface system

Power amplifier is the core equipment of power in the loop real time simulation system and its main function is to amplify the RT-LAB small signal into strong electrical signal, such as 380V three phase voltage. Power amplifier is required to have the ability of wide frequency range output for simulating harmonics. Power amplifier is also needed to have the capacity of four-quadrant operation, simulating different grid operation states.

Flexible interface system adopts pluggable connection device. It can connect different renewable energy power generation units to the power amplifier, also can realize the multiple power generation units connecting to one power amplifier.
2.3. **Renewable energy power generation units**

Renewable energy power generation units include wind turbine generators, photovoltaic power system, energy storage battery, gas turbine generator, MMC-HVDC, LCC-HVDC etc. These generation units are real physical experimental platform and are connected to power amplifier output port through the flexible interface system. The electromagnetic transient course is reflected veritably. Furthermore, the accuracy and reliability are both improved by adopting real physical experimental platform.

With the wind power generation units as an example, this platform use the coaxial connection motor system to simulate the wind turbine generator, the permanent magnet synchronous motor as the drive motor for simulating the mechanical system and the MPPT function. The 10kW double fed induction generator is used as the generator, the rotor back-to-back converter controlled by the real-time simulation controller dSPACE, which is based on the simulink programming environment. The control strategy only need to be set up in the MATLAB/SIMULINK environment, then can be downloaded directly to the dSPACE controller for physical experiment.

2.4. **Other equipments**

Other equipments mainly include the programmable AC supply, large power voltage drop device, micro-grid, three phase RLC load etc. These equipments provide grid environment and experimental environment.

3. **Wind power generator inertia control principle**

Wind power generation with traditional control method has no inertial response ability compared to the regular synchronous generator. The larger the grid scale is, the wind power generation equivalent inertia is smaller, therefore, the grid short-term frequency stability will be influenced and wind power penetration would also be restricted. Adopting the inertia control can make the wind turbine operating like a regular synchronous generator, strengthening the short-term frequency stability of the power grid[12].

![Image](image_url)

**Figure 3.** Doubly fed induction generator real time simulation platform.

Based on the power in the Loop Real Time Simulation Platform, the wind power generator inertia control experiment requires wind power generation experimental platform, which is connected to the RT-LAB real time simulation system through the power amplifier and flexible interface system. The structure of the experiment platform is shown in Figure 3. The grid mathematical model which is established in the RT-Lab, is used to study the grid frequency supporting of inertia control algorithm.
3.1. Basic principle of inertia control

The function of the drive chain of the wind turbine is to translate the kinetic energy of the air into mechanical energy which could be transmitted to wind generator. The mechanical power captured by the wind turbine can be expressed in the following way [13]:

\[ P_m = 0.5 \rho C_p(\lambda, \beta) \pi R^2 v_w^3 \]

(1)

Where, \( P_m \): mechanical power that wind turbine captured, \( W \); \( \rho \): air density, \( kg/m^3 \); \( v_w \): wind speed, \( m/s \); \( R \): wind wheel radius, \( m \); \( \pi R^2 \): swept area, \( m^2 \); \( C_p(\lambda, \beta) \): the wind power utilization coefficient, which is decided by the tip speed ratio \( \lambda \) and the pitch angle \( \beta \). The tip ratio refers to the ratio of the line speed to the wind speed at the blade tip of the wind turbine:

\[ \lambda = \frac{\omega R}{v_w} \]

(2)

The \( \omega R \) is the speed of the wind wheel, \( rad/s \). According to the formula (1), the wind power captured by the wind turbine is related to wind speed, air density, swept area of blade and wind power utilization coefficient. Among them, only the wind power utilization coefficient can be controlled by adjusting the blade tip speed ratio and pitch angle. In the simulation, the approximate analytic expression can be used to describe the wind power utilization coefficient [14]. In this paper, we use the following common approximation, which is related to blade tip speed ratio and pitch angle, to express \( C_p \):

\[
\begin{align*}
C_p(\lambda, \beta) &= a_0 \left( \frac{a_1}{\lambda} - a_2 \beta - a_3 \right) e^{a_1/\lambda} + a_4 \lambda \\
\lambda &= \frac{1}{\lambda + a_5 \beta} \frac{a^2}{\beta^2 + 1}
\end{align*}
\]

(3)

For a given pitch angle, there is a best tip speed ratio of \( \lambda_{opt} \), and the corresponding wind power utilization coefficient is the largest. Therefore, when the input wind speed changes, you can adjust the speed of the wind wheel to maintain the best tip speed ratio to capture the maximum wind energy, which means MPPT control.

In this paper, the model of fan drive chain is modeled by simple mass model [15]. In this model, the blade, wheel hub, low speed drive shaft, gear box, high speed drive shaft and generator rotor are equivalent to a mass block, and the corresponding dynamic equation is

\[ 2H_m \frac{d\omega_e}{dt} = T_m - T_e - D\omega_e \]

(4)

In the model, \( Hm \) is the inertial time constant of mass block; \( D \) is the equivalent mass block self damping coefficient; \( \omega_e \) is the angular velocity of mass block; \( T_e \) is the electromagnetic torque of an induction generator; \( T_m \) is the mechanical torque captured by a fan. In this model, the losses between the mechanical power captured by the fan and the actual output mechanical power are all equivalent to the damping factor \( D \) of the mass. Document [15] also introduces more accurate dual mass and three mass model, which can be used to study the torsional vibration of wind turbine system. This paper does not involve this content. Therefore, a simpler model of simple mass model is adopted.

The realization of the virtual inertia control method is shown as Figure.4. It is most simple to PD control strategy. The virtual inertia control is used to simulate the natural inertia response of traditional synchronous generator. A frequency, active power increment \( \Delta P_f \) are offered as shown in (5), which the \( \Delta f_e \) is the system frequency deviation, \( K_{pf} \) and \( K_{df} \) are proportional coefficient can be set. The control structure is shown in Figure 4, where LPF refers to the low pass filter [16].
\[ \Delta P_{IL} = -K_{df} \frac{d\Delta f}{dt} - K_{pf} \Delta f \]  

(5)

**Figure 4.** Inertia control strategy.

4. Inertia control experiment based power in loop simulation

4.1. Inertia control in the loop real simulation platform

The wind power generation inertia control experiment platform is shown as Figure 5. Because the large scale power grid with renewable generator is impossible to test in real power grid, the large scale power grid model is pure digital and established by using simulink. This simulink model is downloaded into RT-Lab. The model include one DFIG wind farm, two synchronous generator, three loads. The detail parameters is shown in Table 1.

| Element                  | Rated Power (MW) |
|--------------------------|------------------|
| Wind farm                | 300              |
| Synchronous generator1(SG1) | 1200            |
| Synchronous generator2(SG2) | 1200            |
| LoadA                    | 200              |
| LoadB                    | 200              |
| LoadC                    | 300              |
| Equivalent Physical wind-generator | 300            |
| \(K_{pf}\)               | 0.5              |
| \(K_{df}\)               | 300              |

As shown in Figure 5, besides the pure digital grid model running in RT-Lab, there are still a physical 10kw wind generator experimental platform. The structure of the physical platform is described in chapter 2.3. The inertia control strategy is run in the controller of the physical platform. Between the physical platform and the RT-Lab platform is the power amplifier. The physical wind generator is connected to the power amplifier and put the wind power into it. So the power amplifier becomes a grid to the wind generator. The power that the wind generator output is sampled and calculated by amplifier, then transfer to RT-Lab. For example, the physical wind generator output 10kw, the amplifier get the value then transform to RT-Lab, the models in RT-Lab treat the 10kw as 300MW by proportional enlarge. The RT-Lab output the voltage of the node where the physical wind generator connected. The node voltage is transfer to power amplifier between \(\pm 10V\). For example, if the connected node is 380V, then the DA chip output \(\pm 8V\) to the power amplifier, then the power amplifier out 380V to physical wind generator. The output power of the physical wind generator is modeled as a current source in the RT-Lab model and this power is max 300MW, that means there is
300MW wind generator with inertia control in the grid model running in RT-Lab. The aim of the experiment is to explore that how inertia control of wind generator influence the system frequency.

**4.2. Inertia control experimental results based on power in the loop real time simulation**

For validating the inertial control, the whole system operate in stability until 3.5s. The load A begins to increase from 300MW to 465MW in 3.5s. Then the system frequency begin to drop. The Figure 6 a-e show the system frequency transient process with df/dt inertia control and without inertia control.

When the loads is increased, the power grid frequency is decreased, if the physical wind generator has no ability of inertia control, it unable to support the power grid short-term frequency because the active power has no change, as is shown in Figure 6 (a). With the inertia control, when the loads increase to 465MW, the active power of the physical wind generator is increased and the maximum increment is 100 MW, which has provided efficient power support for power grid frequency, as is shown in Figure 6 (a).

Figure 6 (b) and Figure 6 (c) have shown SG1 and SG2 rotating speed response on the condition that physical wind generator farm with and without df/dt inertia control. It can be seen that when the loads increase to 465MW, power grid frequency goes down rapidly. And because of lot of wind generator, the power grid inertia is also decrease, so the minimum frequency point is also declined. However, the frequency dynamic characteristic is greatly improved after the inertia control strategy has been added to the physical wind generator, the minimum frequency point has been increased. Because the physical wind generator control system has restricted the inertia response time, the output active power is decreased and the grid frequency is decreased twice obviously when the inertia control is ended at 12s. Thus, when the wind power penetration is high, the problem of frequency secondary fall should be avoided because of the rotating speed recovery of wind turbine. From Figure 6 (d) and Figure 6 (e), it can be seen that the primary frequency modulation process has been apparently slowing down after the physical wind generator has been added to the inertia control.

**5. Conclusions**

The power in loop real time simulation platform can be used to analyze many something problems of renewable power. In this paper, the whole PHIL platform include RT-Lab, four quadrant power amplifier, flexible interface, many kind of generator unit, etc. With this structure of platform, something can not be tested in real power grid could be tested in the platform, such as inertia control of wind generator. A large scale power grid model is established in RT-Lab by pure digital simulink. The physical wind generator with inertia control is connected to power amplifier. With this structure, the inertia control wind generator supporting the large scale power grid frequency when loads increase strongly is realized. The PHIL is a feasible tools can be used to analyze something problems about renewable power and large scale power grid.
Figure 6. The real-time simulation results of the inertia control
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References
[1] Rongjun Ding, Weihua Gui, Gaohua Chen 2008 Real-time hardware-in-loop simulation of electric locomotive ac drive system(in chinese) China Railway Science 04 96-102
[2] Choi C, Lee W 2012 Analysis and compensation of time delay effects in hardware-in-the-loop simulation for automotive PMSM drive system IEEE Transactions on Industrial Electronics 59(9) 3403-3410
[3] Lucia O, Urriza I, Barragan L A, et al 2011 Real-time FPGA-based hardware-in-the-loop simulation test bench applied to multiple-output power converters [J] IEEE Transactions on Industry Applications 47(2) 853-860
[4] Majstorovic D, Celanofigurevic I, Teslic N D, et al. 2011 Ultralow-latency hardware-in-the-loop platform for rapid validation of power electronics designs [J] IEEE Transactions on Industrial Electronics 58(10) 4708-4716
[5] Honghao Guo, Bo Zhou, Jichen Li, Fangshun Cheng, Le Zhang 2009 Real-Time Simulation of BLDC-based Wind Turbine Emulator Using RT-LAB[C] Proceedings of the conference ICEMS2009 1-6
[6] Xiaotian Wu, Tongzhen Dai, Wenjing Xiao 2013 The wind power generation grid side converter real time simulation based on RT-LAB(in chinese) Power electronics 47(10) 17-19
[7] Daqiang Bi, Fangyuan Chang,Ke Chang, Wind power generation integration hybrid simulation system based on RT-LAB”(in chinese) Journal of Power Supply 6 36-41
[8] Morren, J, et al. 2006 Wind turbines emulating inertia and supporting primary frequency control IEEE Transactions on Power Systems 21 1433-434
[9] Liu Z, Feng L, Mei S, et al. 2016 Application of Extended State Observer in Wind Turbines Speed Recovery After Inertia Response Control[J] Proceedings of the CSEE
[10] Tapia A, Tapia G, Ostolaza J X, et al. 2003 Modeling and Control of a Wind Turbine Driven Doubly Fed Induction Generator[J] IEEE Transactions on Energy Conversion 18(2) 194-204
[11] Pak L F, Dinavahi V 2009 Real-Time Simulation of a Wind Energy System Based on the Doubly-Fed Induction Generator[J] IEEE Transactions on Power Systems 24(3) 1301-1309
[12] LIU Zhangweil, LIU Feng, MEI Shengwei, BI Daqiang, YAO Yaxin 2016 Application of Extended State Observer in Wind Turbines Speed Recovery After Inertia Response Control [J] Proceedings of the CSEE 36(5) 5
[13] Tapia A, Tapia G, Ostolaza J X, et al. 2003 Modeling and control of a wind turbine driven doubly fed induction generator[J] IEEE Transactions on Energy Conversion 18(2) 194-204
[14] Slootweg J G, de Haan S W H, Polinder H, et al 2003 General model for representing variable speed wind turbines in power system dynamics simulations[J] IEEE Transactions on Power Systems 18(1) 144-151
[15] Li Hui, Han Li, Zhao Bin, et al. 2008 Effect of equivalent models of wind turbines on analysis results of transient stability for wind generator systems[J] Proceedings of the CSEE 28(17) 105-111(in Chinese)
[16] Conroy J F, Watson R 2008 Frequency response capability of full converter wind turbine generators in comparison to conventional generation[J] IEEE Transactions on Power Systems 23(2) 649-656