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A power hardware-in-loop based testing bed for auxiliary active power control of wind power plants

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ABSTRACT

Auxiliary active power control (AAPC) of wind power plants (WPP) has been an emerging subject of modern power systems. However, there is currently lack of appropriate platform to test AAPC performances of an actual WPP. Under the background, this paper presents a testing bed for AAPC in both frequency regulation and damping control of WPP. The main novelty is that the platform is designed based on power hardware-in-loop (PHIL) technologies. PHIL technologies enable a physical WPP to integrate to a virtual real-time power system, which is simulated with StarSim software. The technologies combine the advantages of software and hardware simulations. Based on the testing bed, this paper compares the frequency regulation and damping control performances of an aggregated wind farm integrated to an isolated system. The PHIL simulation results demonstrate the strength of the platform, which extends the flexibility of system configurations of software simulation to an actual physical WPP experiment.

1. Introduction

With the increasing wind penetration in power systems, auxiliary controllers needed for wind power plants (WPPs) are becoming more significant for the integration as well as secure operations of wind power plants. Those auxiliary controllers are technically related to the regulations of grid frequency, voltage, and even damping oscillations of wind power systems [1–4]. Specifically less inertia and anti-oscillation capacities of wind generator, result more frequency fluctuations when conventional generators being replaced by WPPs. In this way auxiliary active power control (AAPC) has drawn much attention for enabling wind plants to participate in grid frequency and damping controls of power systems.

According to field or numerical studies [4–7] for AAPC in frequency regulation, wind generators have been proved to be capable of participating within system inertial response via an inertial emulator [4,5], within primary frequency regulation via a droop controller [5] and within secondary frequency regulation via a deloading controller [6,7]. Also for AAPC in damping control, power system stabilizer (PSS) added to wind generator [8,9] proves efficient to prevent power grid oscillations.

As stated in [10,11], AAPC can have significant influence on dynamic behavior of power systems, especially those with high percentages of conventional generators replaced by WPPs. For secure operation concerns, performances of AAPC must be fully tested prior to their deployments in an actual power system. Currently, there have been several testing methods proposed. In study [12], one method based on software simulation is presented to test the existing Irish All-Island system with the integration of wind power. A method for parameter optimization is then developed based on the simulation testing results. Several software such as Simulink [9,16], DigSILENT [7], and package DSA$^{\text{Tools}}$ [13] are widely used to test AAPC performance in corresponding cases. One more method is based on hardware simulation or offline recording, such as the apparatus namely Gridsim used by State Grid of China [14]. The apparatus utilizes an IGBT-based voltage source to emulate a recorded frequency sag in order to test corresponding power responses of wind generators. In comparison with software simulations, hardware-based testing results are more persuadable and not strongly dependent on model accuracies of WPPs. However, especially for damping control, this offline testing cannot fully reveal the additional damping effects of WPPs on power system. So in laboratory, for AAPC in damping control, theory analysis such as Eigenvalue investigation [15] and software simulation [16] are mainly selected to verify the efficiency of the AAPC in WPP damping control.

Nevertheless, neither software nor hardware based testing method is fully capable of satisfying real-world requirements. It is because software simulation results strongly rely on model accuracies of power system components, and pure hardware testing

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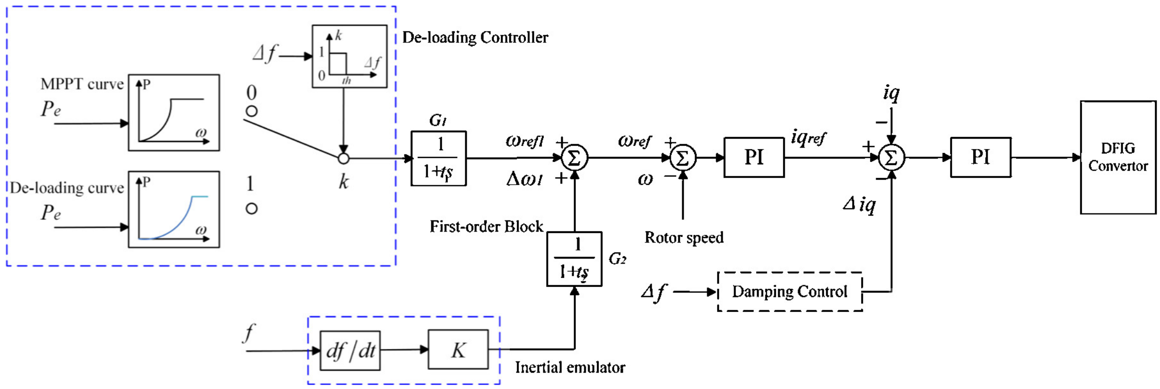

Fig. 1. Modified AAPC for a real DFIG.

lacks of flexibility on establishing a complex power system. In order to overcome these drawbacks, this paper proposes a novel testing bed based on power hardware-in-loop (PHIL) technologies. The PHIL testing bed combines the advantages of software and hardware simulations, and is able to conveniently establish a complex system in a real-time simulator while testing an actual WPP via a specially designed PHIL interface. Considering these features, PHIL can be a convenient simulation testing method prior to a device's deployment as introduced by CAPS in Florida [17], Kansas [18], and Germany [19]. So we consider PHIL based facility for AAPC testing which concentrates on coupled simulation of power grid and physical WPP is a new approach in contemporary wind turbine industry and research.

The paper extends the main idea, introduced in [20] with both control schemes and numerical results. The outline of the paper is organized as follows: In Section 2, AAPC scheme consisting of frequency regulation and damping control is reviewed with a brief explanation of the reason that the control scheme cannot be conveniently tested in a pure-hardware testing environment. Section 3 then introduces a configuration of the PHIL testing bed and Section 4 shows the performance of the PHIL interface via two experiments of amplitude error and time delay testing. In Section 6, an isolated power system case is studied to demonstrate the application of the platform as well as the efficiency of the AAPC scheme.

2. Auxiliary active power control scheme

This section introduces AAPC in frequency regulation and damping control separately and testing method for the control strategies is discussed at the end.

2.1. Frequency regulation

One classic frequency control of DFIG (doubly-fed induction generator, a Type III WPP) is illustrated in Fig. 1. The initial design of the controller is published by Jenkins [2] and Peas Lopes [6], the design is somewhat modified without the loss of generality in order to meet our actual experiment environment. In active power loop, the machine's active power output P_e is feedback to get the output ω_{ref1} through a P–ω curve block and a first-order filter block. And the rotor speed reference ω_{ref}, which is derived by ω_{ref1} is tracked by the machine. After maintaining the rotor speed around ω_{ref}, the machine can track the predefined curve and extracts desired power from turbine.

There are generally two control loops in the proposed scheme. One control loop is the inertial emulator, which takes grid frequency f as feedback to emulate inertial responses of conventional generators. When frequency decreases, the control loop introduces an auxiliary signal $\Delta\omega_1$ on ω_{ref1} to enable the DFIG decrease its rotor speed ω and temporarily release rotor kinetic energy to participate within primary frequency regulation.

Another control loop is the de-loading controller which makes the DFIG operating point deviate from an optimal curve, i.e., maximum power point tracking (MPPT) curve by over speeding. Therefore de-loading method is out of service when rotor speed reaches its maximum speed limit, set at 1200 rpm in this paper, during high wind scenario. Moreover there can be different de-loading curves, which are day-ahead scheduled by wind farm operator, but only one curve is assigned to each WPP at one specific time instance. Under this assumption, a DFIG is capable of permanently increasing its active power output via tracking the optimal MPPT curve so as to participate within the secondary frequency regulation. As shown in Fig. 1, the tracking curve is selected according to the grid frequency deviation, i.e., if the frequency drops below a threshold, the MPPT curve is selected otherwise the DFIG is kept to track the de-loading power curve. Moreover it is assumed that threshold *th* (Hz) is related to wind power penetration *wpf* and de-loading factor *dlf*. To make it simple, the relationship can be written in a linear formula as shown in (1). Parameters of the controller are defined in appendix.

$$th = wpf \times K_1 + dlf \times K_2 + K_3 \qquad (1)$$

In order to make rotor speed return to MPPT operation point tenderly, a first-order block G1 with a time constant of 1.5 s is in series with the de-loading controller. In the same way the added block G2 helps prevent a dramatic change of rotor speed ω.

2.2. Damping control

Fig. 2 explains a typical wind turbine-damping controller added to its active power control loop in Fig. 1. This damping controller mainly consists of a gain block, a washout filter, and a lead–lag compensator. Given parameter restriction of testing DFIG, only system frequency deviation Δf can be feedback to enable the controller modulate the machine's active power output, thus suppressing the system oscillation. Parameters of the controller are attached in appendix.

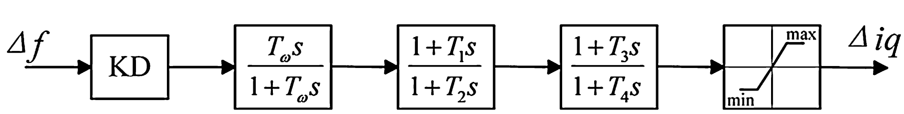

Fig. 2. Block diagram of the classical damping controller.