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Improvement of grid frequency dynamic characteristic with novel wind turbine based on electromagnetic coupler

Rui You [a], Braulio Barahona [b], Jianyun Chai [c], Nicolaos A. Cutululis [d], Xinzhen Wu [a, *]

[a] Department of Electrical Engineering, Qingdao University, 308 Ningxia Road, Qingdao, China
[b] Department of Civil, Environmental and Geomatic Engineering, ETH, Zurich, Switzerland
[c] Department of Electrical Engineering, Tsinghua University, Beijing, China
[d] Department of Wind Energy, Technical University of Denmark, Frederiksborgvej 399, Roskilde, Denmark

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ABSTRACT

A synchronous generator is directly coupled to grid in the novel wind turbine drive train concept based on electromagnetic coupler (WT-EMC). Similarly to conventional power plants, WT-EMC has inherent (inertial) grid frequency support capability, albeit rather limited due to its configuration. Additional power should be generated in response to a grid frequency drop in order to improve the dynamic characteristic of the grid frequency. In this paper, a novel control strategy for WT-EMC to improve the dynamic characteristic of grid frequency is proposed. The principle is to detect active power imbalance in the grid and then rapidly regulate the output power of WT-EMC. Based on the calculated electromagnetic torque of the synchronous generator in WT-EMC—acquired faster than the calculated grid frequency—the synchronous generator mechanical torque is controlled to track its electromagnetic torque to stabilize the rotor speed, therefore directly improving the grid frequency. The proposed control strategy effectiveness is firstly tested through simulations and then validated on a specially built experimental platform.

1. Introduction

Wind energy is one of the fastest growing industries nowadays and it will continue to grow worldwide, as many countries have plans for future development. The increased share of wind energy in power systems over the last decade is directly reflected in the wind turbine grid connection requirements and the new technologies necessary to conform to them [1,2]. Such technical requirements describe the desired operational behaviour and corresponding control tasks so that wind turbine generators can perform similar to conventional power plants where synchronous generators are used [3]. They define the necessary capabilities for active and reactive power regulation, fault-ride through (FRT) and operation within specific grid voltage and frequency ranges. The focus of this paper is on active power regulation of a novel wind turbine drive train concept to support grid frequency.

Modern wind turbine generators are nowadays partially (Type 3) or fully (Type 4) decoupled from the grid by power converters, therefore very different from conventional power plants [4,5]. These configurations can result in the reduction of the power system inertia and increased rate of change of frequency (ROCOF) given active power imbalances [6–8]. This is a particular concern to transmission system operators, especially under the circumstance of higher share of wind power generation and lower share of conventional power plants available to support the grid frequency. So the importance of grid frequency support from wind power generation is emphasized [9].

A power imbalance in the power system, for example a sudden load change, is reflected instantaneously as a change in the electromagnetic torque of synchronous generators in conventional power plants. This causes a mismatch between synchronous generator mechanical torque and electromagnetic torque resulting in the change of the synchronous generator speed and rotor rotational energy, which effectively limits the ROCOF. The ROCOF value depends on the power system inertia, which consists of the sum of all synchronous generators and loads inertias. In conventional power plants the speed error signal between measured generator speed and reference value is amplified and integrated to produce a

* Corresponding author.
E-mail addresses: yourui1984@163.com (R. You), wuxinzhen81@163.com (X. Wu).

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control signal which actuates the main steam supply valves in the case of a steam turbine, or gates in the case of a hydraulic turbine. As a result, the synchronous generator mechanical torque changes at a slow rate because of the large inertia of the rotor, resulting in the decayed changes of synchronous generator speed and grid frequency [10]. In order to mimic such inertial response, short-term additional power can be injected into the grid from variable speed wind turbine responding to a frequency drop [11]. The additional torque is calculated typically in two ways: inertial control and droop control [12–14]. The additional torque term is proportional to the derivative of grid frequency d*f*/d*t* for the former and to the frequency deviation from the nominal value for the latter. However, mimicking inertia based on the measured frequency is a delay procedure and the precise, fast frequency measurement (especially d*f*/d*t* for the first method) is not easily implemented, resulting in a delay of the power regulation after a grid power imbalance occurs.

In Rui et al. [15], a variable speed wind turbine based on electromagnetic coupler (WT-EMC) was proposed, a novel concept employing a synchronous generator directly coupled to grid. Therefore in principle, power system requirements for grid connection are easier to meet with this wind turbine. Type 3, Type 4 wind turbine and WT-EMC were compared comprehensively in Ref. [15]. Compared with Type 3 and Type 4 wind turbines, WT-EMC has better capabilities in terms of transient overload, FRT and grid voltage support, and inherent grid frequency support capability. However given the reduced inertia of synchronous generator in WT-EMC due to its drive train configuration, additional power should also be generated in short time after occurrence of power imbalance to improve grid frequency dynamic characteristic. Droop controller and inertial controller were proposed to enhance the grid frequency support capability of WT-EMC, and their feasibilities were verified in simulations [16]. Compared with the grid frequency which is the input signal of Type 3 or Type 4 wind turbine grid frequency support controller, the synchronous generator speed is more stable and can be accurately measured. For that reason, it was used to detect active power imbalance in the grid and calculate WT-EMC additional output power in Ref. [16]. However, the delay of wind turbine output power regulation after grid power imbalance was not improved.

In this paper a novel control strategy of WT-EMC, completely different from the one in Ref. [16], is proposed to detect grid power imbalance and then rapidly regulate the power output of WT-EMC. Based on the calculated electromagnetic torque of the synchronous generator in WT-EMC, acquired faster than the calculated grid frequency (which is necessary for the grid frequency support control of Type 3 and Type 4 wind turbines) and than the synchronous generator speed (used for WT-EMC grid frequency support control in Ref. [16]), the synchronous generator mechanical torque is controlled to track its electromagnetic torque to regulate WT-EMC output power and ultimately improve grid frequency dynamic characteristic. A quantitative comparison between the grid frequency improvement using WT-EMC with the control strategy proposed and that using Type 4 wind turbine with frequency support control is not included. Since the focus of the simulation and experiment presented in the following sections is to validate the effectiveness of the proposed control strategy for WT-EMC.

The paper is organized as follows. Firstly, WT-EMC configuration is introduced and a novel grid frequency support control strategy is proposed. Secondly, a power system model consisting of a wind farm composed of WT-EMCs and a conventional power plant is described. Then the experimental platform built and its configuration are presented. The main simulation and experimental results that demonstrate the effectiveness of the proposed control strategy are presented. Finally, the analysis is concluded.

2. WT-EMC and its grid frequency support control with electromagnetic torque track

In WT-EMC an electromagnetic coupling speed regulating device (EMCD) is used to connect the high speed shaft of gearbox and rotor shaft of synchronous generator, and transmit torque from gearbox to synchronous generator. EMCD consists of an electromagnetic coupler and a converter, and its typical structure is shown in Fig. 1. The electromagnetic coupler is a squirrel cage induction motor essentially with two rotating shafts, one of them (front shaft) connected with the gearbox and the other (back shaft) with the synchronous generator. The converter controls the relative speed between the two shafts and electromagnetic torque of electromagnetic coupler. In Ref. [17] a 1.5 MW WT-EMC experimental platform was built and EMCD power transmission efficiency was measured. The efficiency was found to reach up to 98% around the rated condition.

Compared with synchronous generators in conventional power plants, the inertia of the synchronous generator used in WT-EMC is relatively smaller. This is because the electromagnetic coupler decouples the gearbox side and the synchronous generator side of drive train. Therefore, only the back shaft in Fig. 1—which is composed of one rotor of the electromagnetic coupler and the rotor of the synchronous generator—contributes to the inertia. This results in a limited inherent grid frequency support capability, compared to what is possible considering the large rotational inertia of the wind turbine rotor. However, because the converter is used to apply the electromagnetic torque of the electromagnetic coupler, which is the mechanical torque on the synchronous generator rotor, a fast change of synchronous generator mechanical torque can be achieved to mimic inertia and support grid frequency.

The back shaft motion equation is shown in equation (1).

$$T_m - T_{SG} - B_b\omega_b = J_b\frac{d\omega_b}{dt} \tag{1}$$

where T_{m} is the synchronous generator mechanical torque, applied by converter; T_{SG} is the synchronous generator electromagnetic torque; ω_{b} is the back shaft speed; B_{b} is the back shaft friction factor and J_{b} is the back shaft moment of inertia. According to equation (1), it can be seen that if the change of T_{m} is controlled to track the change of T_{SG} ($\Delta T_{\mathrm{m}} = \Delta T_{\mathrm{SG}}$) once T_{SG} changes, the back shaft speed (synchronous generator speed) can be kept approximately constant. Thereby WT-EMC contribution to support grid frequency can be achieved.

Based on the analysis above, a WT-EMC grid frequency support control strategy is proposed. The overall structure of WT-EMC including the control loops is illustrated in detail in Fig. 2. A flowchart is shown in Fig. 3. Because grid active power imbalance is

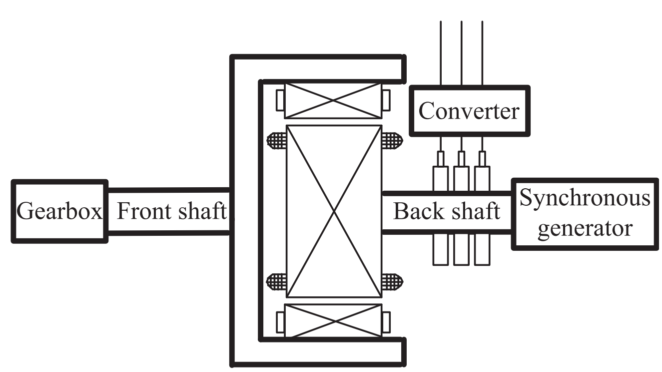

Fig. 1. Schematic diagram of EMCD typical structure.