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Active power control design for supporting grid frequency regulation in wind farms ☆

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ABSTRACT

Among renewable energy sources, wind power is expected to contribute a larger and rapidly growing portion of the world's energy portfolio. However, the increased penetration of wind power into the power grid has challenged the reliable and stable operation of the grid. This motivates new opportunities in the design and development of novel control schemes capable of actively maintaining the necessary balance between power generation and load, which in turn regulates the grid frequency when plenty of winds are available. This paper presents two active power control schemes that are developed based on adaptive pole placement control and fuzzy gain-scheduled proportional-integral control approaches. The active power control is conducted collectively across a wind farm to provide rapid power response while maintaining safe structural loading on turbines' components. The proposed active power control schemes are evaluated and compared by a series of simulations on an advanced wind farm benchmark model in the presence of wind turbulences, measurement noises, and grid load variations. It is further demonstrated that the mentioned schemes are able to tolerate probable occurrence of sudden imbalance between generation and load due to relevant faults/failures in the wind farm or electric grid.

1. Introduction

Renewable energy technologies are clean and sustainable sources of energy that can serve as alternatives to meet the world's increasing demand for efficient, reliable and affordable energy needs in the years ahead. Among renewable energy sources, wind power is expected to contribute a larger and rapidly growing portion of the world's energy portfolio. Over the past few decades, much research and development have been done on wind power in order to minimize the cost of wind energy. In this regard, larger and more flexible wind turbines have been designed and installed in remote locations such as offshore regions. Moreover, to lower the high costs of operation and maintenance due to high rate of failures of wind turbine components, advanced condition monitoring, diagnosis, and fault-tolerant and efficiency control solutions have been proposed recently. For example, in Badihi, Zhang, and Hong (2014) and Badihi, Zhang, and Hong (2015), the authors employ fuzzy modelling, identification, and control techniques to design and develop integrated fault diagnosis and fault-tolerant control schemes for addressing sensor faults and actuator faults in a wind turbine, respectively. In Shi and Patton (2015), an observer-based fault-tolerant control scheme within a linear parameter varying framework is proposed for an offshore wind turbine system. Another work presented in Shaker and Patton (2014) proposes a sensor fault-tolerant control approach based on fault estimation and compensation for an offshore wind turbine described via Takagi–Sugeno multiple models. In Simani and Castaldi (2014), a fault-tolerant control scheme that employs a robust actuator fault estimation approach using adaptive filters is proposed.

Based on international statistics, many large wind farms have already been installed and more in all forms of onshore and offshore are planned to be integrated into the power grids throughout the world (Global Wind Energy Council). Since wind energy is naturally a fluctuating source of power which relies on the prevailing wind, the efficient and reliable connection/integration of wind turbines and wind farms to the grid has always been an important issue for grid operation. As long as only small-scale power units of wind turbines are installed and powering the network, wind power only has a small influence on power fluctuations in the network and in turn can easily be integrated. However, the increased penetration of wind power into the power grid has challenged the reliable and stable operation of the grid. This situation has required some transmission systems operators (TSOs) to formulate grid code requirements exclusively for countries and regions with relatively isolated grids and high levels of wind power penetration. Basically, these grid codes require wind farms to

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behave as active and controllable components which embrace more responsibility in grid operation. This means that wind farms have to participate in grid frequency and voltage regulation through control of active and reactive power, respectively. So, the codes provide specific information such as operational ranges for voltage and frequency as well as control requirements for active and reactive power. For example, in Canada, Hydro-Québec grid code for wind farm interconnection requires that wind farms with installed capacity of more than 10 MW shall have active power control capability for at least 10 s to provide power/frequency regulation in response to grid frequency deviations higher than 0.5 Hz (Hydro-Québec, 2005).

In order to meet the ever evolving grid code requirements on frequency variations and to support efficient and reliable integration of wind power, active power control (APC) strategies are essential for actively maintaining the necessary balance between power generation and loads, which in turn regulates the grid frequency when plenty of winds are available. Research related to APC of wind energy generation has been focused on control approaches that are able to meet the grid code requirements and satisfactory response time for tracking power commands without exceeding the safe operating limits of the turbines. Most of the APC approaches rely on modification of generator torque with respect to measurements of the variations in grid frequency and possibly the rate of these variations. In Gowaid, El-Zawawi, and El-Gammal (2011), Juankorena, Esandi, Lopez, and Marroyo (2009), Ma and Chowdhury (2010), the wind turbine operates at a higher than optimal tip-speed ratio to provide an overhead power reserve for addressing possible deviations in frequency. The authors in Morren, Haan, Kling, and Ferreira (2006) present an augmented control approach that employs two proportional control loops based on variations in grid frequency and the rate of these variations for modifying the generator torque command. In addition to the modification of generator torque, the blade pitch angles can also be modified for providing APC. An integrated torque and blade pitch control approach is developed in Gautam, Goel, Ayyanar, Vittal, and Harbour (2011). Here, the change in grid frequency is used by a proportional torque controller while a blade pitch controller assists in primary response by regulating pitch angle as needed to avoid large variations in mechanical power during frequency transients. Droop curves are typically used to characterize the change in active power output of a generator governor caused by a change in grid frequency. The application of droop curves to APC of wind turbines has also been studied in the literature, for example see (Aho, Pao, Buckspan, & Fleming, 2013; Buckspan, Aho, Fleming, Yunho, & Pao, 2012; Chang-Chien, Hung, & Yin, 2008; Yuan, Chai, & Li, 2010).

From a control system development viewpoint, APC in wind turbines can be developed at both individual turbine and entire wind farm levels. Prior research on wind turbine APC has been mostly focused on APC at individual turbine level that means performing active power control on individual turbines separately. However, performing APC collectively across a wind farm can be advantageous in terms of faster response and recovery to grid frequency deviations (Aho et al., 2012). Therefore, considering APC at the entire wind farm level, this paper presents two control schemes aimed at tracking various forms of power schedules and loads, while maintaining grid frequency against any sudden imbalance between generation and loads, which is referred to as *frequency event*. A frequency event is typically caused by sudden variations in electrical loads, new generation allocation, disconnection of generators, and disturbed generation due to faults and failures. The two APC schemes are developed based on adaptive pole placement control and fuzzy gain-scheduled proportional-integral (PI) control approaches. A main advantage of the proposed schemes is their stand-alone structures that do not complicate the wind turbines' conventional control loops for easier acceptance and validation & verification by wind energy industry for commercialization. Furthermore, the proposed schemes can operate in the same range of wind speeds as wind turbines' standard baseline control systems while considering the practical safe operating limits of the turbines.

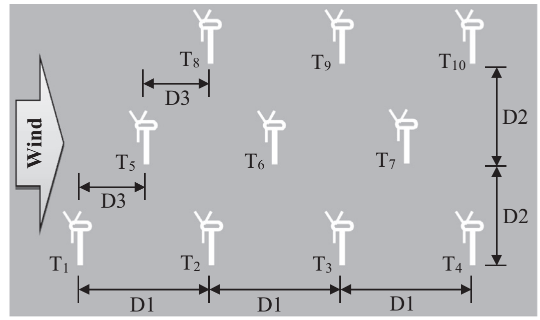

Fig. 1. Wind farm layout ($D1 = 600$ m, $D2 = 500$ m, $D3 = 300$ m).

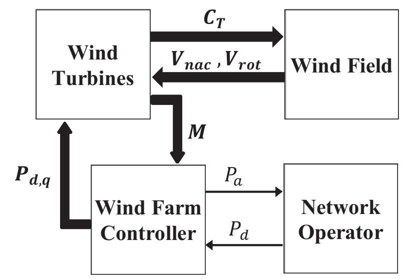

Fig. 2. Illustration of the overall wind farm structure (this figure is based on (Soltani et al., 2009)).

The effectiveness of the proposed APC schemes is evaluated by a series of simulations on an advanced wind farm benchmark model (Soltani, Knudsen, & Bak, 2009), in the presence of wind turbulences, measurement noises, and grid loads variations. It is also demonstrated that the mentioned schemes are able to tolerate probable occurrence of realistic frequency events.

The remainder of the paper is organized as follows: In Section 2, the used wind farm benchmark model is briefly overviewed. The overall framework used for electrical grid frequency regulation and active power control based on fuzzy gain-scheduled PI control and adaptive pole placement control are described in Section 3. Section 4 presents the simulation results with some comments and discussions. Finally, conclusions are drawn in Section 5.

2. The wind farm benchmark model

This paper considers an advanced wind farm simulation benchmark model developed in the EU-FP7 project, AEOLUS (Soltani et al., 2009). The model allows control designers to develop and investigate farm level control solutions under various operating conditions for an optional quantity and layout of wind turbines installed in a wind farm. In the benchmark model, sensor models are updated as noise-contaminated, uncertain measurement systems. Moreover, different wind fields with arbitrary mean wind speeds and turbulence intensities can be generated and applied in order to facilitate the assessment of the robustness features of any control solution under external disturbances. The default wind farm layout is shown in Fig. 1.

Fig. 2 illustrates the overall structure of the wind farm under consideration. As it is shown in Fig. 2, this benchmark model is composed of four major components:

(A) Network operator The network operator determines the active power demand P_d required for safe and reliable connection of wind farm to the electrical grid. The baseline model for network operator can function in different modes such as: absolute, delta, and frequency regulation modes. Basically, in the frequency regulation mode used in this paper, the measured grid frequency $f_m(k)$ is used

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