

Kinetic Energy Recovery of a Wind Energy Doubly-Fed Induction Generator for Grid Frequency Support[†]

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Abstract: Synchronous generators provide an inherent inertial response to frequency deviations because of their huge revolving mass that is electro-mechanically tied to the electrical network. Contrariwise, the power converters isolate the revolving mass of variable speed wind turbines from the electric network. Therefore, they are not able to provide an inherent inertial reaction to frequency events on the electric network. This reduces the effective network inertia, which is essential for maintaining the power system's frequency. To address this problem in cases of using a wind energy doubly-fed induction generator, this study introduces a kinetic energy recovery controller to the rotor-side converter.

Keywords: Variable-speed wind turbine (VSWT); frequency support; kinetic energy recovery

1. Introduction

A prevailing number of megawatt-class Wind Turbine Generators (WTGs) are Variable Speed Wind Turbine (VSWT) generators [1]–[3]. VSWTs, do not exhibit a natural inertial response to frequency events due to their mechanical and electrical control systems being decoupled [4]–[6]. Supplementary frequency control functions can be used to create a connection between the power production of the WTGs and the network frequency [7]. The virtual synchronous machine (VSM) is a concept of controlling power electronic interfaces on a power system, to replicate the most desirable properties of a synchronous machine [8]–[11]. VSM needs to use the virtual inertia using a buffer of enough stored energy [8]. A systematic literature review (SLR) from 2015 to mid-2022 was done by the authors to verify the validity of the study in this research field [12]. This paper will present a kinetic energy recovery controller to the wind turbines using DFIG to emulate the inertial response of synchronous generators for grid frequency support. This paper is organized as follows; section 2 presents the mathematical modeling of the system's components and proposed controller, section 3 presents a case study with the IEEE-14 bus system to verify and test the adaptive frequency controller, and section 4 presents the conclusions.

2. Mathematical Modeling

The nominal frequency of a transmission network is maintained at by the balance between generation and consumption. The frequency stability of a network is a time-varying attribute where a power system is expected to continue operating following a disturbance that results in a severe imbalance between generation and load [1]. Traditional synchronous generators will naturally exhibit an inertial response [2]. This dynamic

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inertial response of a synchronous generator can be described mathematically by the swing equation (1).

$$\frac{2H}{\omega_s} \frac{d^2\delta}{dt^2} = P_m - P_e \tag{1}$$

Where, H is the inertia constant, ω_s is the synchronous speed, and P_e and P_m are the respective electrical and mechanical powers respectively. It is found that the power that can be extracted from the wind, P_m , is half the air density multiplied by the cube of wind velocity [14] and can be expressed by (2) where: ρ is the density of air; r the radius of the wind turbine; C_p the wind turbine power coefficient; v_{wind} the wind speed; λ the tip speed ratio and β the pitch angle.

$$P_m = \frac{1}{2} \rho \pi r^2 v_{wind}^3 C_p(\lambda, \beta), \tag{2}$$

The wind turbine power coefficient, C_p , has a maximum theoretical limit of 59.3% called the Betz limit [15]. The wind turbine power coefficient shows the effect of the rotor speed and pitch angle variation on the aerodynamic power [16]. The Tip Speed ratio, λ , can be calculated by (3) [17] where ω_r is the angular velocity of the wind turbine rotor.

$$\lambda = \frac{\omega_r r}{v_{wind}} \tag{3}$$

The pitch control is used to control the speed and the output power of the wind turbine by adjusting the pitch angle. The pitch control system is shown in 1[18].

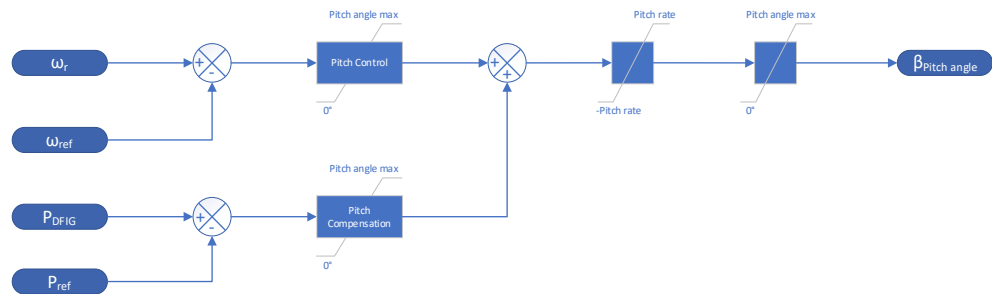


Figure 1. Pitch control system block diagram.

The reference rotor speed, ω_{ref} , is 1.2 pu (with the synchronous rotational speed as the base value) while the output power of the wind turbine is not less than 0.75 pu (with a base value of the rated mechanical power of the wind turbine) [18]. The rotor reference speed, ω_{ref} , has a minimum value of 0.7 pu.

$$\omega_{ref} = -0.67(P_{DFIG})^2 + 1.42(P_{DFIG}) + 0.51, \tag{4}$$

The mechanical power and the electrical output power of the stator is computed by (5), where: P_m is the power transmitted to the rotor that has been captured by the wind turbine, ω_r is the rotational speed of the rotor and P_s is the electrical output power of the stator [19].

$$P_m = T_m \omega_r P_s, \tag{5}$$

For a lossless generator, the mechanical equation which describes the dynamic behaviour of the rotor mechanical speed in terms of the mechanical torque, T_m , and the electromagnetic torque, T_{em} , is given by (6) [20].

$$J \frac{d\omega_r}{dt} = T_m - T_{em}, \tag{6}$$

This study will be using the average model since as the focus of this study is the interaction between the DFIG control system and the power system [21]. The frequency support controller shown in

2 emulates an inertial response by injecting additional power during a frequency disturbance by increasing the d-axis rotor reference current.

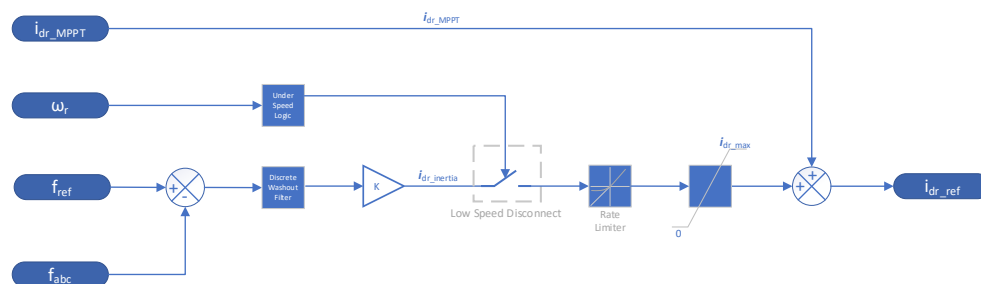


Figure 2. Adapted Frequency Support Controller.

3. Case study

The test system used in this study is based on the modified IEEE 14-bus system is used in [17] is shown in Figure 3. The modified IEEE 14-bus system consists of two voltage zones, connected by T1, T2 and T3. Busses 1 through to 5 form part of the 132 kV zone while busses 6 through to 14 form part of the 33 kV zone. The modified 14-bus system includes synchronous generators, 11 static loads and an aggregated wind farm model. The aggregated wind farm subsystem consists of 80, 1.5 MW class DFIG WTs. The effects of the frequency support controller to consecutive disturbances, is studied below.

3.1. Case study: Wind speed condition of 10 m.s⁻¹ with a consecutive disturbance

A generator generating 130 MW, is tripped at 10 s and an additional generator, is tripped at 50 s with wind speed conditions of 10 m.s⁻¹. Figure 4 (a) shows the frequency support of an MPPT operated DFIG-based wind farm. The frequency nadir of first disturbance is 49.125 Hz while the frequency nadir of caused by the second disturbance is 49.288 Hz.

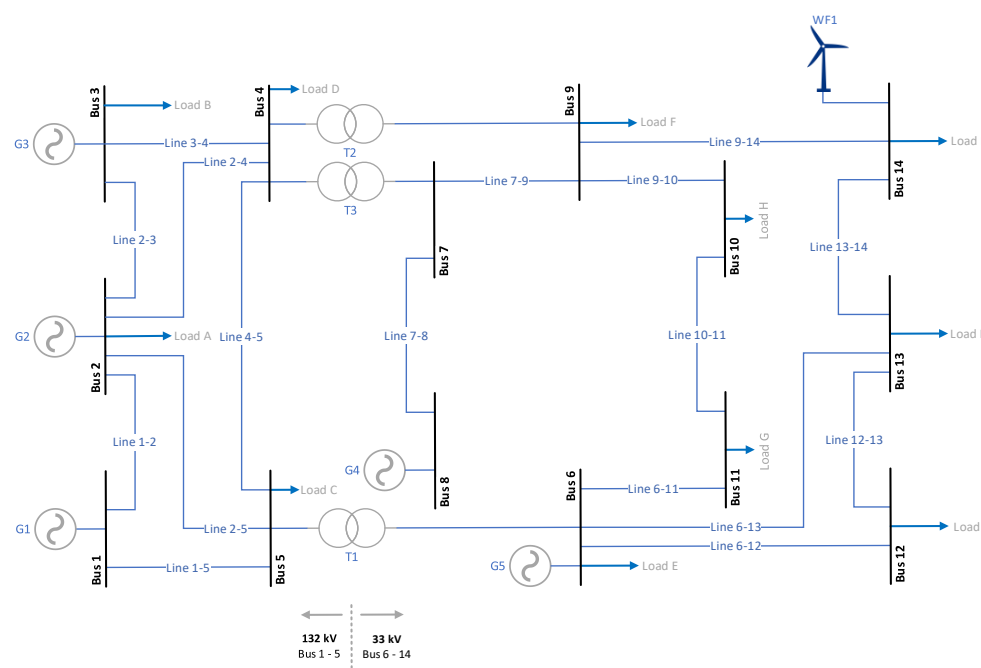


Figure 3. Single Line Diagram of a modified IEEE 14-Bus System [17].

Figure 4 (b) shows the results of the DFIG-based wind farm partaking in frequency support. In Figure 4 (b), the first frequency nadir of 49.4 Hz is reached at 13.8 s following

the first disturbance at 10 s. The system frequency recovers to 49.62 Hz prior to the second disturbance occurring and following this second disturbance at 50 s, a frequency nadir of

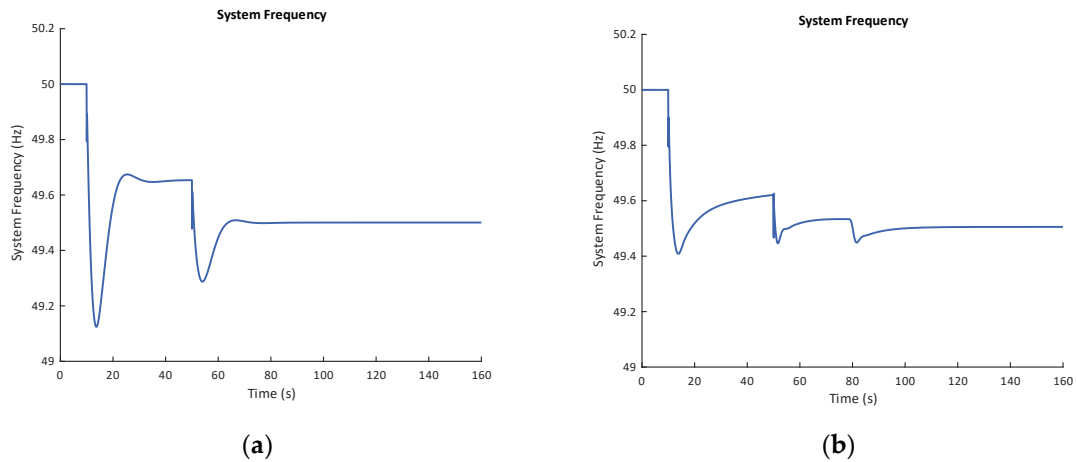


Figure 4. (a) System Frequency with no frequency support from DFIG-based wind farm; (b) System Frequency with frequency support from DFIG-based wind farm.

49.44 Hz is reached at 51.6 s. The system frequency recovers 49.53 Hz at 79 s following the consecutive disturbances. However, at this point the system frequency succumbs to another frequency deviation as the rotor speed reaches its minimum speed and under speed logic reduces the frequency support controller contribution to zero.

The WPP output of the MPPT operated DFIG-based wind farm is shown in Figure 5 (a). The MPPT operated DFIG-based wind farm shows no significant increase in output power when subjected to consecutive disturbances. While the WPP output of the DFIG-based wind farm with frequency support is shown in Figure 5 (b). The WPP output begins to rise rapidly when the disturbance occurs at 10 s and peaks at 114.6 MW. After the peak, the WPP output begins to decline as the system frequency approaches a new steady state but continues to decline below the pre-disturbance WPP output power of 72.55 MW to 61.2 MW at 39.2 s due to the rotor recovering its speed. When the second disturbance occurs at 50 s, the WPP output power rises to 84.8 MW at 51.8 s to overcome the frequency disturbance caused by the second generator tripping. The WPP output power begins to decline as the system frequency begins to recover and continues to decline below 61.2 MW as the rotor has deviated considerably from its optimal speed. The WPP output power reaches a minimum output of 47.2 MW at 80.3 s as the under-speed logic negates the contribution frequency support controller. The WPP output power has a non-monotonic increase to 69.1 MW as the rotor speed recovers.

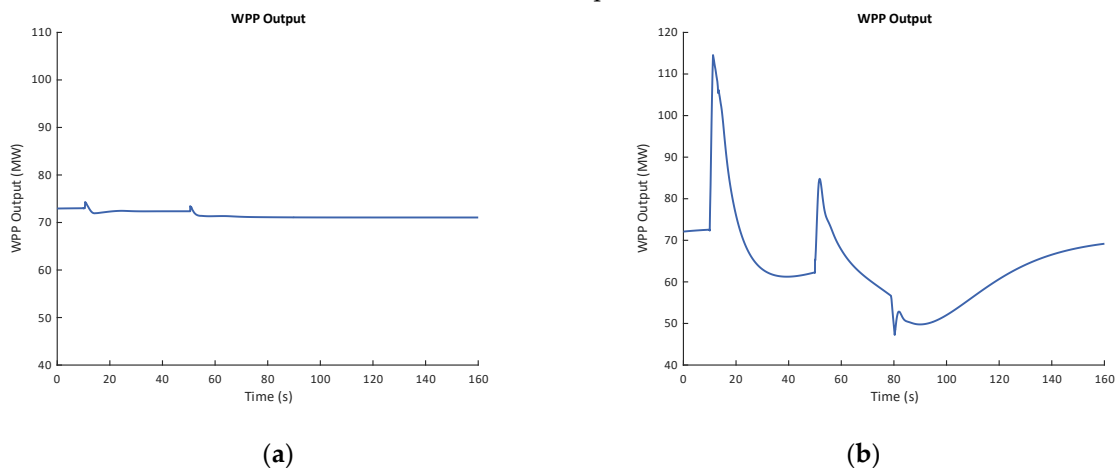


Figure 5. (a) Case 3 WPP Output with no frequency support from DFIG-based wind farm; (b) Case 3 WPP Output with frequency support from DFIG-based wind farm.

The rotor speed of the MPPT operated DFIG-based wind farm in Figure 6 (a) shows no significant deviation in rotor speed following two consecutive disturbances at 10 s and at 50 s. However, the rotor speed of the DFIG-based wind farm with frequency support shown in Figure 6 (b), begins to decrease when the disturbance occurs at 10 s to a minimum speed of 0.87 pu at 28.9 s. The rotor speed recovers to a speed of 0.94 pu prior to the second disturbance at 50 s which occurs during the rotor recovery phase. The rotor speed begins to decline at the instance of the second as the kinetic energy is recovered to support the system frequency. The rotor speed following the second disturbance reaches a minimum speed of 0.75 pu at 79.6 s when the under-speed logic is triggered. This prevents any further exchange of kinetic energy from the rotor to electrical energy and leads to the third frequency drop to 49.45 Hz seen in Figure 6. The rotor recovers monotonically from its minimum speed to 1.05 pu.

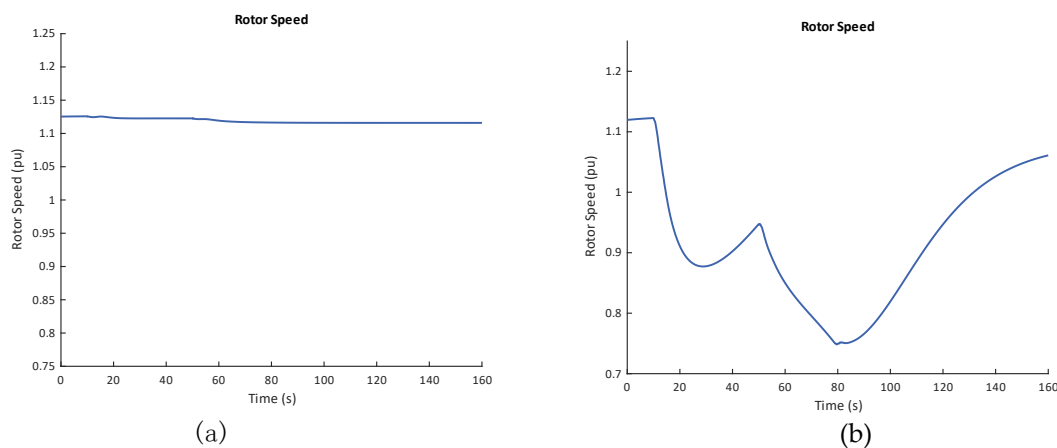


Figure 6. (a) Rotor Speed with no frequency support from DFIG-based wind farm; (b) Rotor Speed with frequency support from DFIG-based wind farm.

4. Conclusions

The frequency support controller emulates an inertial response by temporarily raising the active power output of the wind turbine generator during a frequency disturbance. The additional energy required for the temporary overproduction of active power during a frequency disturbance is obtained by recovering the kinetic energy of the spinning mass of the wind turbine generator. Future work should aim to extend the frequency support performance of the WTG in low wind conditions and varying wind speed conditions.

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