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An Active PID-Based Inertial Control of a Doubly-Fed Induction Generator

Thelfa Ahmad[1], Tim Littler[2], Wasif Naeem[3]
School of Electronics, Electrical Engineering and Computer Science
Queen's University Belfast, Belfast, UK

tahmad01@qub.ac.uk[1], t.littler@qub.ac.uk[2], w.naeem@qub.ac.uk[3]

***Abstract*— The increasing level of wind power integration using doubly fed induction generators (DFIGs) has implications for local frequency support as a consequence of decoupling between DFIG rotor speed and grid frequency. To ensure reliable and stable power system operation with DFIG integration, supplementary inertial control strategies are required. Conventional inertial control algorithms which use the rate of change of frequency (RoCoF) and frequency deviation loops (droop loop) require great effort to determine appropriate gains suitable for all power grid and wind speeds. In this paper, the influence of supplementary inertial control loop parameters on the inertial response and power system frequency are analysed. An active control strategy is proposed for frequency regulation using variable gains in the frequency deviation loop for the inertial controller. The variable gain control approach is shown to actively respond to system changes to improve the performance. The controller is compared with the widely used PID method. The proposed method is shown to enhance the frequency nadir and guarantee steady DFIG operation.**

Keywords*— *wind energy generation; doubly-fed induction generator (DFIG); frequency control; inertia; kinetic energy; rate of change of frequency (RoCoF); frequency nadir; variable gains.

I. INTRODUCTION

Measurement of power system frequency provides an important parameter to monitor balance between electrical supply and demand [1].The objective of frequency control is to maintain operating frequency as closely as possible to the nominal frequency [2]. The network frequency will change when the total active power generation differs from the total active power required by a load. The system frequency is controlled by balancing the generation of power against the load demand on a second-by-second basis. A conventional power plant with synchronous generation has an inherent capability to control frequency, because of significant inertia [3]. The response duties of a conventional power plant can be split into a primary response and secondary response. The primary and secondary responses are defined as the additional active power delivered by automatic governor action from a generating unit that is available at 10 seconds and 30 seconds, respectively after the event and which can then be sustained for 20 seconds to 30 minutes, respectively [4]. At this point, if the frequency declines below the specified value, an under frequency load-shedding relay causes an additional frequency decline. Hence the frequency nadir can be regarded as a significant indication of network stability and reliability [5].

Recently there has been an increased interest in doubly fed induction generator (DFIG) based wind turbines due to their wider operating range as they are able to reach maximum efficiency for a wide range of wind velocities. Consequently, a DFIG is adapted to change its rotational speed constantly and hence output power at different wind speed [1]. Many of the large wind turbines that are now commercially available are of this type. Operating a large number of DFIG based wind turbines displaces conventional synchronous generators and this in turn creates a range of new problems such as reducing system inertia and increasing RoCoF. This reduces the ability to control the frequency of the system due to DFIG decoupling between the mechanical and electrical systems; thus preventing the generator from responding to system frequency changes. This is undesirable when there are a large number of DFIG wind turbines operating, especially in periods of low load and on smaller power systems (e.g., Ireland).

The frequency of a power system with low inertia will certainly change rapidly for abrupt variations in generation or load unlike conventional generators, which reduces the ability to control the frequency of the system. As a consequence, modern variable speed wind turbines (VSWTs) do not participate in control of system frequency. However resolution of problem can help ensure reliable and wide-area stable operation of the power grid [6]. To release kinetic energy stored in rotating masses during an event, a significant amount of research on inertial controllers has been conducted in order to regulate frequency. The basic form of inertial control loop involves using RoCoF [3], [6]. In [7]-[9], the RoCoF and frequency deviation loops (droop loops) were used to improve the frequency support of DFIG on the basis that when system frequency changes e.g. due to generator tripping or sudden increase in load, output active power should respond rapidly through supplementary inertia control.

The RoCoF loop (*df/dt*) operates due to the faster release of kinetic energy resulting from its dependence on the derivative of the power system frequency (*df/dt*). However, as a result, the effect of RoCoF decreases with time because of the contribution of the conventional generation. In addition, it tends to improve the frequency nadir. Hence it can be said that the RoCoF supplementary loop of a DFIG is able to support the system frequency, decreasing it gradually whilst at the same time improving its minimum value. In [7] and [8], the RoCoF and frequency deviation loops were used to improve the frequency support of DFIGs. These schemes were shown to have a greater impact than a single loop inertial controller. Thus, inertial control combined with a frequency deviation loop, extensively improves the frequency nadir as a result of releasing greater total output power. Thus, during the initial stage of an event the RoCoF loop is more dominant than the droop loop. On the contrary, during the frequency rebound stage, the droop loop is dominant and the RoCoF loop provides negligible contribution.

In published literature, normally, the gains of the supplementary control loops are maintained. A large gain provides enhanced frequency nadir, however it may cause over-deceleration of the rotor speed. Therefore, supplementary control loops should not be used when the rotor speed reaches its minimum value, to avoid over-deceleration of the rotor speed. This can lead to significant wind turbine generator (WTG) tripping, consequently causing a drop in the power system frequency. On the other hand, a small gain provides a slight improvement in the frequency nadir, whilst ensuring stable operation of a WTG [10].

Existing literature reveals limited work on controller parameter adjustment, particularly during transient conditions. However, it is acknowledged that significant performance improvement can be made by appropriate adjustment of inertial controller parameters. The purpose of this work is therefore to preserve acceptable frequency nadir whilst ensuring reliable operation. To achieve this, an adaptive inertial control strategy has been developed which utilises different values of deviation and RoCoF loop control gains (active gains) based on change of frequency. This variable gain control approach actively responds to changes in the system to improve control and to alter conditions by releasing a larger quantity of kinetic energy stored in the rotating mass of the DFIG during the initial stage of an event.

II. SIMULATION STUDIES

Simulations have been carried out in Matlab/Simulink to validate the inertial controller scheme and to illustrate the capability of DFIG to simulate system inertia in case of any disturbance such as a sudden increase in load. A four machine power grid was used, which consists of three conventional power plants (M1, M2, M3), two combined loads (L1, L2) and a DFIG-based wind farm rated at 300 MW (1.5 MW each). M1, M2, M3 are rated at 400 MW, 400 MW and 500 MW respectively whereas the two loads L1 and L2 are rated at 800 MW each. The wind speed is assumed to be 12 m/s whilst the DFIG is originally under the MPPT control.

A. Case Study 1: Conventional inertial control of a DFIG

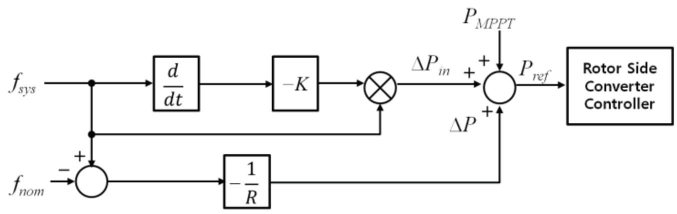
In this work, the RoCoF and frequency deviation loops were used to improve the frequency support of DFIG as suggested in [7]-[9]. The conventional inertial control is depicted in Fig.1 where the first loop is the RoCoF loop (ΔP_{in}) whilst the second one shows the frequency deviation loop or droop loop (ΔP), and with K and $1/R$ being the gains of RoCoF and deviation loop, respectively.

From the figure, ΔP_{in} can be written as,

$$\Delta P_{in} = -K \cdot f_{sys} \cdot \frac{df_{sys}}{dt} \quad (1)$$

The gain ΔP emulates the frequency deviation loop of a synchronous generator, and it can be expressed as,

$$\Delta P = -\frac{1}{R}\left(f_{sys} - f_{nom}\right) \quad (2)$$



f_{sys}, f_{nom}: system frequency and nominal frequency

Fig.1 Inertial controller schematic for the DFIG [11]

The inertial controller for the DFIG-based wind turbine works as follows. When the power system frequency drops below its nominal value for any disturbance, such as sudden increase in load, the inertial response control loop (the active power reference generated by the RoCoF loop ΔP_{in} and active power reference generated by the frequency deviation loop ΔP) sends additional active power ΔP_{ref} to the DFIG active power reference P_{ref} control loop as shown in Fig.1. Therefore, ΔP_{ref} become positive and consequently P_{ref} increases. Thus, the kinetic energy stored in the rotating mass in the DFIG is released and consequently the rotor speed of DFIG w_r decreases according to Eq. (3), [1].

$$P_m - P_e = P_m - (P_{MPPT} + \Delta P + \Delta P_{in}) = J w_r \frac{dw_r}{dt} \quad (3)$$

where $P_{m,}$ P_e, P_{MPPT} represent the mechanical power, electromagnetic power and maximum power point tracking, respectively.

During the initial stage of an event the RoCoF loop ΔP_{in} is dominant as the RoCoF has a large value and the droop loop ΔP is less dominant. Contrarily, during the frequency rebound, the droop loop ΔP is dominant and the RoCoF loop renders a smaller contribution. Therefore, both the RoCoF and frequency deviation loops were employed to support system frequency. This will positively influence system performance as opposed to using the loops acting separately [12].

The introduction of the two loops is more effective when power system frequency deviation increases thus they are widely used in DFIG–based wind turbines. As mentioned earlier, the gains in both loops schemes (K and $1/R$) are generally held constant. In general, a large gain provides an enhanced frequency nadir, however it may cause over-deceleration of the rotor speed. Conversely, a smaller gain provides a slight improvement in frequency nadir whilst ensuring stable operation of the WTG [10].

B. Case study 2: The effect of controller parameters values at different times during the transient period

In this case, the load was increased by 10% at t = 50s, as a consequence of the power imbalance (the generation power against the load demand). Therefore, the system frequency drops suddenly as shown in Fig. 2 (a). Rotor acceleration will occur if the wind turbine torque (mechanical torque) T_m exceeds the generator torque (electromagnetic torque) T_e. It is clear that the induction machine torque depends on the difference between the rotor rotational speed, w_r and magnetic field rotational speed, w_s. The difference, as a fraction of magnetic field rotational speed, is known as the slip, S:

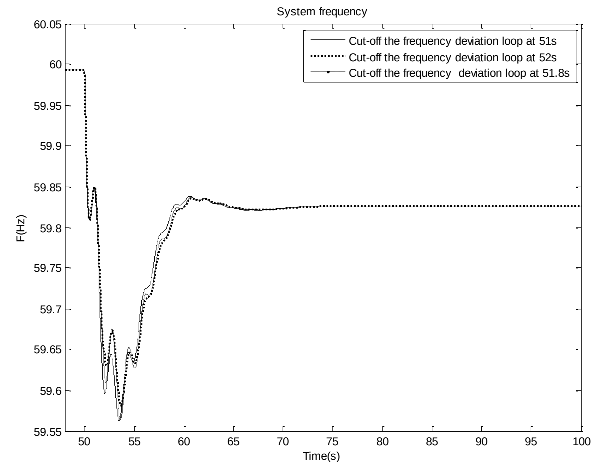
$$S = \frac{w_s - w_r}{w_s} \quad (4)$$

$$\frac{P_m}{w_r} - T_e = J\frac{dw_r}{dt} \quad (5)$$

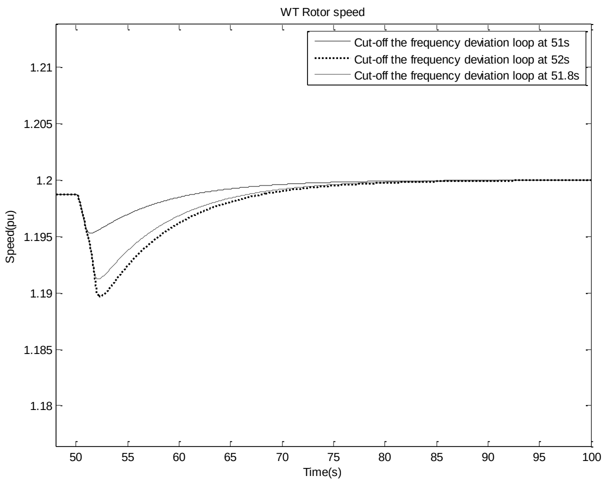
$$T_m - T_e = J\frac{dw_r}{dt} \quad (6)$$

In Eqs. (4), (5) and (6) above, $T_m, T_e, J,\ P_m$ are the mechanical torque, electromagnetic torque, moment of inertia and input mechanical power, respectively [1].

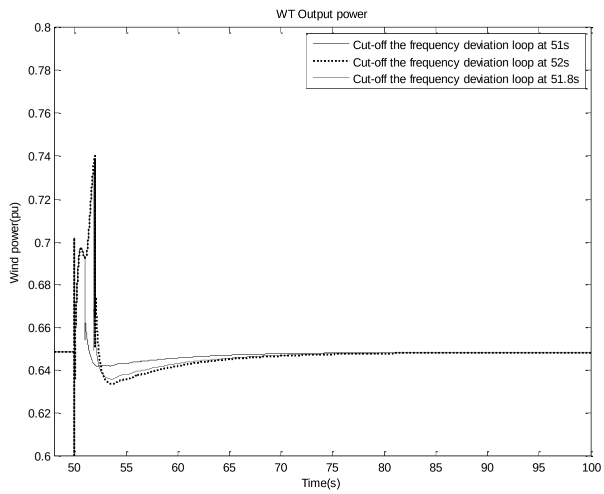
In a normal situation when the output electromagnetic torque is equal the input mechanical torque, $\frac{dw_r}{dt}$ is zero. During a frequency drop, when parameters are added to T_e to improve its inertial response, $\frac{dw_r}{dt}$ becomes negative and therefore the rotor speed decreases which releases kinetic energy whilst increasing the DFIG active power output. Therefore the faster the DFIG controller reacts, the quicker it limits changes in the slip; thus causing reduction in the inertia response. Table. 1 shows quantitative analysis of the inertial response, frequency nadir and rotor speed at different times when the control gain is limited. In addition, Fig. 2 illustrates the effect of removing the gain of the speed of inertial control on power system frequency, Fig. 2(a); DFIG rotor speed value, Fig. 2 (b); and inertial response of the DFIG, Fig. 2(c). The results show that when the droop loop is cut off at the initial stage, at t = 51s, the inertial control acts faster, as in Fig. 2 (b) and the electromagnetic torque decreases. Thus the inertial response will be less as in Fig. 2(c); and the frequency nadir is also low.



(a) Power system frequency



(b) Rotor speed variation



(c) DFIG active power output

Fig.2 Inertial response of DFIG in different time of controller speed

Table. 1 Inertial response, frequency nadir and rotor speed value of DFIG in different time of controller speed.

No.	Droop loop cut-off time	Steady state frequency error	Inertial response	Frequency nadir	Rotor speed (min)
	(sec)	(Hz)	(pu)	(Hz)	(pu)
1	50.1	-0.4482	0.6604	59.5518	1.1988
2	50.2	-0.4474	0.6735	59.5526	1.1985
3	51	-0.4381	0.6973	59.5619	1.1953
4	51.8	-0.4364	0.7332	59.5636	1.1912
5	51.9	-0.4287	0.737	59.5713	1.1905
6	52	-0.4199	0.7401	59.5801	1.1897
7	53	-0.3850	0.7405	59.615	1.1830
8	60	-0.3514	0.7405	59.6486	1.1622

At t = 51.8s, the rotor speed decreases to 1.1912 pu whilst the inertial response increases. However, there is a slight improvement in frequency nadir, Fig. 2(a), due to the fact that the $\frac{df}{dt}$ controller loop improves the frequency nadir marginally, unlike the frequency deviation loop, which considerably enhances the frequency nadir. Therefore, from Table 1, it is apparent that the controller parameters of the frequency deviation loop and adjustment of these values at different times during the frequency event can positively impact the frequency nadir. From t = 52s, the rotor speed decreases, thus providing additional kinetic energy in comparison to before, Fig. 2(b) and Fig. 2(c), respectively. Therefore by increasing the speed of the control system, the rotor slip of the DFIG will be less, which will reduce the inertial response.

C. Case study 3: An active frequency deviation loop- based inertial control scheme for the DFIG

In this case, an adaptive inertial control scheme for frequency regulation uses an active gain (variable gain) for the frequency deviation loop. A frequency deviation loop (droop loop) has been chosen here since it allows more total energy discharge [13]. Also, the contribution of this loop is definite and is not influenced by frequency rebound *noise* included in the measured frequency, [10]. The objective of the scheme is to preserve a stable frequency nadir and guarantee steady DFIG operation. This control strategy has been developed to utilize different values of the deviation loop gains based on the RoCoF.

The gain of the RoCoF (K) loop in the proposed scheme is maintained constant while the droop frequency deviation loop gain ($1/R$) (changes with time, based on the RoCoF). As in the previous case, the power system frequency drops suddenly because of the additional load is connected to the power system at t = 50s.

In this scheme, a shaping function was designed to overcome the frequency deviation loops limited contribution during the initial period of an event. Hence, the scheme actively changes its gain value during the time based on the RoCoF to achieve a large value of ΔP; the droop gain should be large during the primary stage of an event and decrease its value with time to avoid over-deceleration of a WTG. The initial value of the droop gain is thus chosen to be 20. This value remains unchanged even when the disturbance starts at t = 50s. At t = 51.3s, the droop gain value is increased to 30 which is then gradually decreased with time until it reaches the initial gain value of 20 at t = 53.54s.

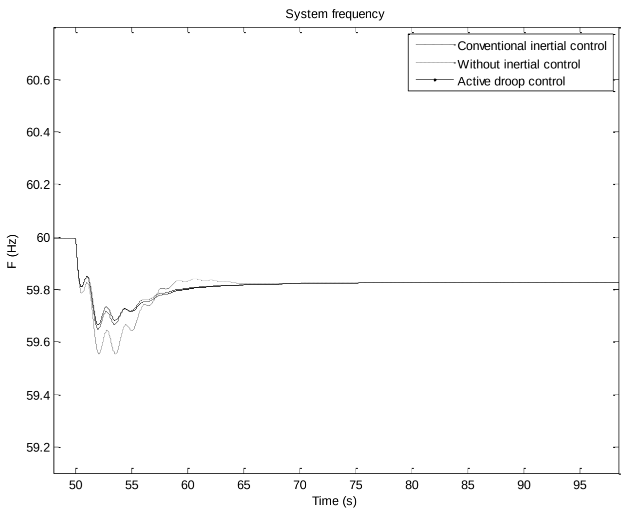
Fig. 3 shows the results for this case. The load is increased suddenly from 1600 MW to 1760 MW at t = 50s. Consequently, the system frequency drops suddenly, as shown in Fig. 3(a). Since there is no additional inertial control added to the power control loop, the rotor mechanical speed is decoupled from the grid frequency. As a result, the DFIG showed little or no inertia and the power system frequency rapidly drops to around 59.5541 Hz. The increased load is compensated by the conventional plant. However, the system frequency then overshoots to around 59.8398 Hz due to the integral gains of the speed controllers in the conventional generators.

Without any inertial control on the wind power plant, the rotor speed remains constant. Also, the active power of the DFIG remains constant at 0.6482 pu as the conventional generators increase their generation to stabilize the effect of additional loading as shown in Figs. 3(b) and 3(c).

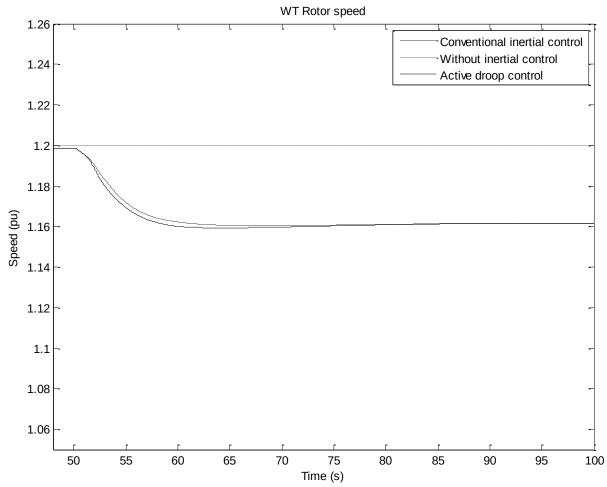
An additional inertial control is introduced to the power control loop (see Fig. 3), such that when the system frequency decreases, an additional power ΔP_{ref} is added to the active power reference P_{ref}, by increasing the torque set point of the DFIG wind turbine. Consequently, the electromagnetic torque increases. As the wind speed is constant, the mechanical torque remains constant, whilst the rotor decelerates as shown in the torque equation shown in Eq. (6.)

Therefore, kinetic energy will be released in this situation. Fig. 3(a) shows that the system frequency nadir is improved from 59.5541 to 59.6468 Hz, because of the sudden increase in the electrical active output power. Since the DFIG mechanical torque power is smaller than its electromagnetic torque power the rotor speed will decrease as shown in Fig. 3(b). In Fig. 3(c), the DFIG increases its output active power from 0.6482 to 0.74 pu.

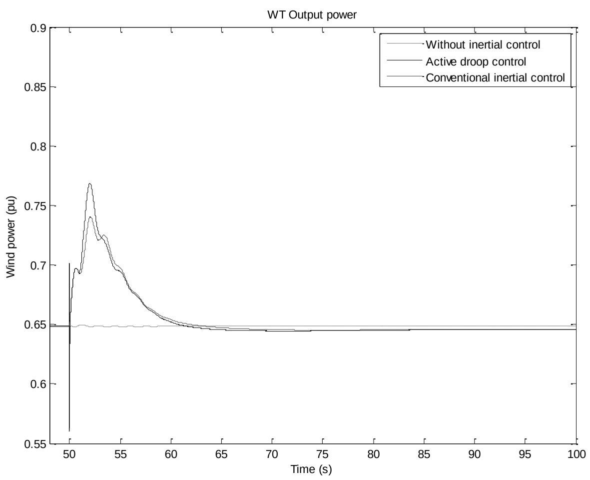
The frequency nadir of the proposed scheme is 59.6657Hz. Thus, the frequency nadir of the proposed scheme is higher than that of the conventional inertial control by 0.0189Hz. Moreover, in the case of the proposed scheme, the oscillation and overshoot are entirely removed, as compared to the conventional inertial control. Therefore the rotor speed will decrease to a value within the operating range. The rotor speed of the proposed scheme is reduced further than that of inertial scheme and reaches 1.1594 pu at 62.79s; whereas for the inertial scheme, the rotor speed reaches 1.1605 pu at 65.5s as shown in Fig. 3(b). The inertial response of the proposed scheme is 0.7686 pu, thus it can effectively render a greater inertial response than that of the inertial scheme by 0.0281 pu. Hence, the proposed scheme limits frequency deviation after the rebound because it releases more kinetic energy than that of the inertial scheme.



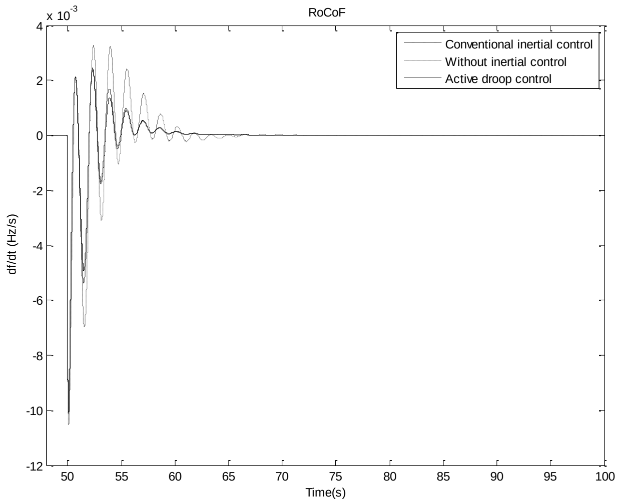
(a) Power system frequency



(b) Rotor speed variation



(c) DFIG active power output



(d) RoCoF

Fig.3 System frequency, rotor speed a Inertial response of DFIG for case study 3

The peak values of the inertial response for the conventional and proposed schemes are 0.7405 pu and 0.7686 pu, respectively. Conversely, the power outputs of the inertial and proposed schemes are identical until 51.02s. Finally, the peak RoCoF values of the proposed scheme are smaller than those of the conventional scheme as indicated in Fig. 3(d). Hence, the proposed scheme is able to preserve the frequency nadir, as desired.

III. CONCLUSION

This paper has investigated the transient performance of DFIG wind turbines for local power system frequency regulation. Based on the evaluation and results, DFIG wind turbines have the capability to support system frequency and emulate inertia by adding supplementary control to the power electronic convertor. The influence of controller parameters for different values at different times during transient periods has also been examined. It is apparent that appropriate adjustment of the frequency deviation controller parameters at different times during a frequency event has a significant impact on the frequency nadir and negative power reference alleviation from the RoCoF loop. Moreover, the paper proposes an adaptive control strategy for frequency regulation using the active gains of a frequency deviation loop-based inertial control. This variable gain control approach actively responds to changes in the system to improve control in comparison to PID control widely used in power systems.

The proposed scheme can preserve the frequency nadir and guarantee steady operation of a DFIG using the frequency deviation (droop) loop based on the ROCOF. Thus, DFIG wind turbines can support system frequency and emulate local inertia by adding supplementary control to the power electronic convertor. The results demonstrated that the proposed scheme increases the frequency nadir compared to conventional schemes and can potentially offer proportionate inertial response to ensure steady DFIG operation.

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References

1. B. Fox et al, *Wind power integration: connection and system operational aspects*, IET, 2007.

2. M.A. Hanley, "Frequency Instability Problems in North American interconnections," *National Energy Technology Laboratory (United States)* 2011.

3. J. Ekanayake, L. Holdsworth and N. Jenkins, "Control of DFIG wind turbines," *Power Engineer*, vol. 17, no. 1, pp. 28-32 2003.

4. Holdsworth, L., Ekanayake, J. B. and Jenkins, N. (2004), power system frequency response from fixed speed and doubly fed induction generator-based wind turbines. Wind energy. 7: 21–35. doi: 10.1002/we.105.

5. B. Delfino, S. Massucco, A. Morini, P. Scalera and F. Silvestro, "Implementation and comparison of different under frequency load-shedding schemes," in *Power Engineering Society Summer Meeting, 2001*, 2001, pp. 307-312 vol.1.

6. J. Ekanayake and N. Jenkins, "Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency," *Energy Conversion, IEEE Transactions on*, vol. 19, no. 4, pp. 800-802 2004.

7. G. Ramtharan, J.B. Ekanayake and N. Jenkins, "Frequency support from doubly fed induction generator wind turbines," *Renewable Power Generation, IET*, vol. 1, no. 1, pp. 3-9 2007.

8. J. Morren, S.W.H. De Haan, W.L. Kling and J.A. Ferreira, "Wind turbines emulating inertia and supporting primary frequency control," *Power Systems, IEEE Transactions on*, vol. 21, no. 1, pp. 433-434 2006.

9. Z. Zhang, Y. Sun, J. Lin and G. Li, "Coordinated frequency regulation by doubly fed induction generator-based wind power plants," *IET Renewable Power Generation*, vol. 6, no. 1, pp. 38-47 2012.

10. M. Hwang, E. Muljadi, J.-. Park, P. Sorensen and Y.C. Kang, "Dynamic droop-based inertial control of a doubly-fed induction generator," *Sustainable Energy, IEEE Transactions on*, vol. PP, no. 99, pp. 1-10 2016.

11. H. Lee, J. Kim, D. Hur and Y.C. Kang, "Inertial control of a DFIG-based wind power plant using the maximum rate of change of frequency and the frequency deviation," *Journal of Electrical Engineering and Technology*, vol. 10, no. 2, pp. 496 2015.

12. J. Lee, E. Muljadi, P. Sorensen and Y.C. Kang, "Releasable kinetic energy-based inertial control of a DFIG wind power plant," *Sustainable Energy, IEEE Transactions on*, vol. 7, no. 1, pp. 279-288 2016.

13. S. El Itani and G. Joos, "Comparison of inertial response implementations in DFIG-based wind turbines," in *Electrical and Computer Engineering (CCECE), 2011 24th Canadian Conference on*, Niagara Falls, ON; Canada, 2011, pp. 000900-000903.