Global Journal of Scientific Researches

Global Journal of Scientific Researches
Available online at gjsr.blue-ap.org
©2016 GJSR Journal. Vol. 4(4), pp. 54-62, 31 August, 2016
E-ISSN: 2311-732X

Combined Inertia and De-loading Frequency Response Control by Variable Speed Wind Turbines

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Received: 25 July, 2016 *Accepted: 10 August, 2016* *Published: 31 August, 2016*

ABSTRACT

The increasing penetration of wind power impacts the frequency stability of power systems .The participation of wind generation in primary frequency control has become a serious concern under study .Due to the lack of contribution of these turbines in grid frequency regulation, control schemes are necessary for wind turbines and power systems to support the frequency control. Wind turbine control methods that enable frequency support and control are presented. The advantages and disadvantages of each method are discussed. This paper presents a novel frequency regulation by DFIG-based wind turbines to combined inertial control, rotor speed control and pitch angle control, under three wind speed mode (low, medium and high). Detailed models are built in MATLAB/SIMULINK and simulation results are compared. Simulation results show that this strategy improves the frequency response after a frequency drop.

Keywords: *Frequency response, variable speed wind turbine, frequency control, doubly fed induction generator.*

INTRODUCTION

The electricity industry worldwide is turning increasingly to renewable sources of energy to generate electricity. Environmental concerns about fossil-fueled conventional generators, the desire to increase the diversity and security of fuel supply, and increasing fossil fuel costs are all motivating factors behind this upward trend. Global targets for the reduction of carbon dioxide (CO_2) and other greenhouse gases have been introduced and separate targets for minimum quantities of electricity generated from renewable energy sources have also been established in many parts of the world [1]. Wind is the fastest growing and most widely utilized of the emerging renewable energy technologies in electricity systems at present, with a total of approximately 369 GW installed worldwide at the end of 2014 [4]

The effect of wind generation on the system frequency regulation is one of the most important problems. First, the unpredictable and highly fluctuating wind generation can have consequences in terms of frequency stability. As the wind penetration in a system increases, the randomness and the fluctuation of wind power increase, causing the frequency variations in the power system to increase [2].

Second, modern wind farms are generally equipped with variable speed wind turbines (VSWTs). Variable-speed turbine technologies use back-to-back power electronic converters for the grid connection. The intermediate DC voltage bus creates an electrical decoupling between the machine and the grid. Therefore, variations in grid frequency are not distinguished by the generator rotor and apparent inertia of the power system decreases with increasing wind power penetration [3].

Therefore auxiliary controllers need to be implemented in the converter to relate the electromagnetic torque and frequency for the primary frequency control. Another reason is that traditional doubly fed induction generators (DFIGs) normally operate at maximum power point tracking (MPPT), so they cannot increase their output power beyond the maximum power level [1].

The impact of fluctuations in frequency, is very important in small or isolated power systems that has weak or no connection with other systems.

This paper is structured as following: Section II describes Methods of enabling variable speed wind turbine primary regulation, Section III determines three wind speed regions and demonstrates, Section IV proposes the new strategy of improving variable speed wind turbine frequency response, case model are presented in Section V, conclusions and simulation are given in Section VI and finally the results are elaborated in section VII.

I. Controller Used for Frequency Response in Wind Power

Frequency control in power systems is usually shaped of primary and secondary control. Modern power system will require an active participation of wind power generation on the primary and secondary frequency control. Although generators electronically controller and/or electronically connected to the grid do not provide frequency response, this ability can be obtained by adding an extra control to the power converters.

Several control schemes can be describe to enable the wind power generation to provide frequency response, it can be divided into three-level hierarchy including "wind turbine controller", "wind farm controller" and "power system level controller" [5].

In this study, wind turbine controller is described. Wind turbine level controllers enable transient support for the frequency. These controllers can enable the primary frequency control by two strategies: inertial controller and governor controller.

A. Inertia Controller

The goal of the inertia control is to enable temporarily increase power output during frequency disturbance. This control needs some kind of energy storage to be able to increase the power production.

A VSWT can emulate frequency response similar to the inertial response provided by synchronous generator by executing an inertial controller. The inertia controller can be created in two basic methods: Releasing and Fast Power Reserve Emulation. Hidden Inertia is more practical. This controller is a simple control loop added on the power converter controller, it creates an active power control signal following a version of the swing Eq. (1) [6], [7]:

$$P_{Hsyn} = 2H_{syn} f_{sys} \frac{df_{sys}}{dt} \qquad (1)$$

Where P_{Hsyn} is inertial power, Hsyn is express the synthetic or emulated inertia (sec) and f_{sys} is system frequency in per unit. Implementation of releasing hidden inertia controllers is described in Figure 1.

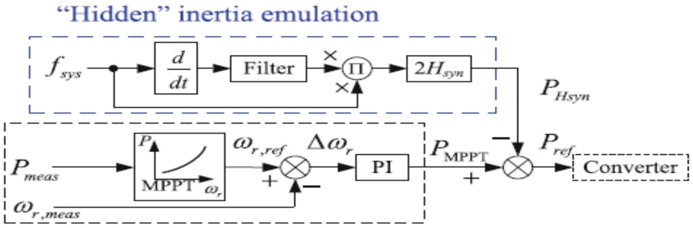


Figure 1. Releasing hidden inertia controller

The wind turbine generator (WTG) can quickly store and release a large amount of kinetic energy in the rotating masses because of the power electronic converter, due to a large amount of inertia and wide rotational speed. The inertia controller helps to reduce the maximum frequency change rate and increases the transient frequency nadir [8]. Comparison with fixed speed wind turbine (FSWT) and conventional generators, the inertia controller releases considerably larger kinetic energy [9].

B. Governor Response Controller

The governor provides the control between frequency and generation power in a generator participating in primary frequency control. The governor of a generator provides the governor response and it is expected to be available within a few seconds (depending on intrinsic time contestants) after system frequency disturbance [5].

1) Droop controller

The steady-state characteristic of the governor controller is defined by the permanent droop (ρ), which define is defined as the change in frequency(Δf), normalized to the nominal frequency(f_{norm}), divided by the change in power output(ΔP), normalized to a given power base, (P_0) [6].

$$\rho = \frac{\Delta f[p.u]}{\Delta P[p.u]} \qquad (2)$$

The inverse of the droop is R and it is referred to as the stiffness of the generator.

$$R = \frac{1}{\rho} = \frac{\Delta P[p.u]}{\Delta f[p.u]} \qquad (3)$$

The droop controller is described by a steady-state frequency characteristic as shown on Figure2 [6].

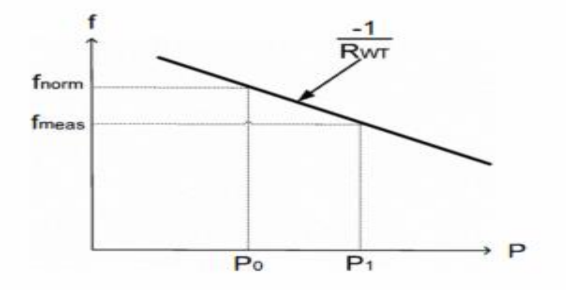


Figure 2. Frequency droop characteristic

The power rising (ΔP) during a sudden decrement on system frequency must be achieved from the kinetic energy of the rotation parts of wind turbine generator, it causes a decrease on rotational speed due to the Maximum Power Point Tracking (MPPT) operation for this reason droop controller require support of other wind turbine components to prevent turbine stall by rotational speed falling too low. The solution to this problem is the use of combined de-loading and droop controls that will describe in section (2-2-2).

Droop controller has not great effect on the initial Rate of Change of Frequency (ROCOF) after frequency disturbance but greatly impacts on the frequency nadir.

2) De-loading Control

The operation of WTG at MPPT state allows the active power output has reached the maximum value at the instant wind speed. However, there are no power reserves from the wind turbine, and using the kinetic energy from the rotor mass of the wind turbine can only provide a short-term frequency droop control.

The de-loading control can enable wind turbines to save some active power as reserves. The active power production in a VSWT can be controlled acting on pitch angle (β) and rotational speed (ω) [10], as consequence, the de-loading operation can be classified by two ways: pitch control (pitching action) and over speeding control.

a) Pitching Control

Pitching Control acts when the rotational speed is move than the maximum value for a high wind speed condition.
A traditional pitch angle controller scheme is shown on Figure 3.

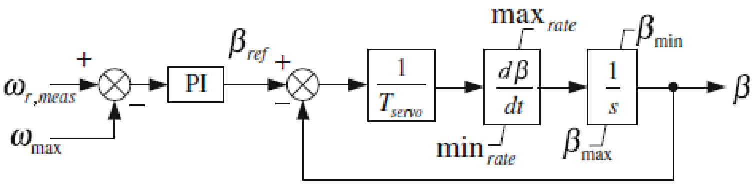


Figure 4. Pitch angle controller [6]

In this study, the rotor speed reference (ω_{ref}) is used instead of the maximum rotor speed which is obtained from the equation (4) [1]:

$$\omega_{ref} = 1.2 + \frac{\Delta P}{0.1 P_{MPPT}} (\omega_{MPPT} - 1.2) \qquad (4)$$

This selection, provides the combined inertia and de-loading strategy that is presented in section 3.
One important aspect of the pitching approach is that response of pitch angle controller is slow because the mechanical time constant of pitch angle controller [8], [11].

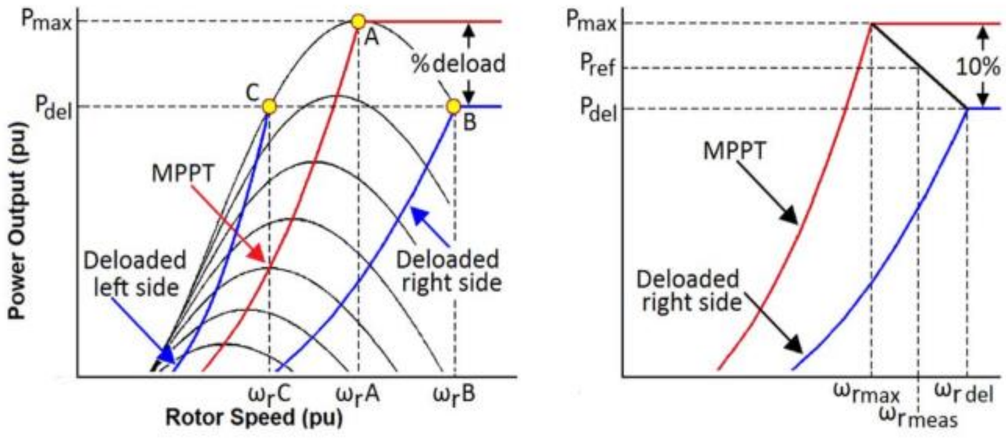
b) Rotational Speed Control

If wind speed and pitch angle be constant, the active power of a VSWT can be reduced from the maximum power point (point A, Figure 4b) by increasing the rotational speed over the MPPT speed (point B), this action is known as over-speeding.

This is a more suitable operation than pitching action when the rotational speed is below the maximum value, and it can protect the pitch blade of wear and tear compared for low wind speeds [12].

Over-speeding operation leads more kinetic energy stored in the blade as consequence if the WTG is equipped with inertia controller, the frequency response is improved.

During low frequency periods, applying the generation margin thus created, the WTG output can be varied between P_{del} (de-loaded power) and P_{max} (maximum power) by varying its rotor speed between de-loaded speed and maximum speed [10].



(a) (b)

Figure 4(a). MPPT and de-loaded power curves of WTG, (b) calculation of power reference for de-loaded operation [10]

In this study, de-loading is 10%. Figure 4(b) shows a 10% de-loading in the right side of the MPPT curve.
For a 10% de-loaded WTG, the power output equals to:

$$P_{del} = 0.9P_{max} \tag{5}$$

Referring to Figure 4(b), the operating power reference of the de-loaded WTG for any rotor speed is calculated as [10]:

$$P_{ref} = P_{del} + (P_{max} - P_{del}) * \left[\frac{\omega_{r\,del} - \omega_{r\,meas}}{\omega_{r\,del} - \omega_{r\,max}}\right] \tag{6}$$

Where
$\omega_{r\,max}$ DFIG rotor speed
$\omega_{r\,del}$ DFIG rotor speed
$\omega_{r\,meas}$ Measured rotor speed
Figure 5 shows a general scheme for a rotational speed controller for a VSWT.

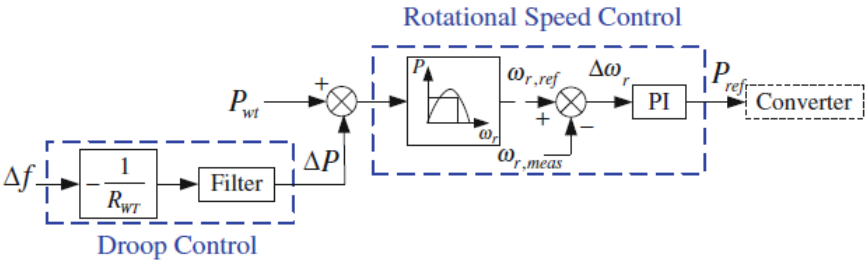


Figure 5. Rotational speed control for VSWT [6]

II. Coordinated control strategies

This study represents the low, medium and high wind speed regions for one type of wind turbines. The wind speed regions are concluded by two factor of wind power/speed curves and reserve margin.

Firstly, the power/speed curves have already been provided by generator manufacturers or general specifications. Secondly, the reserve margin is given by operators or grid codes [1].

Each kind of wind turbines has a special power/speed curves, so, a look-up table in which every reserve margin is in accordance with selected wind speed regions is settle. Therefore according to the reserve margin, the classification of wind speed regions can be looked up from the look-up table.

From the viewpoint of adaptability, the controllers are needed to operate normally at a wide range of wind speeds. This study gives a new classification for the wind speed regions for the aim to regulate DFIGs and coordinate rotor speed and pitch angle controls, which will explained below.

1) Mode 1: low wind speed mode (4 - 10.1 m/s)

At lower speeds than cut-in speed, the wind turbine is paused by the brake. In current study cut-in speed is 4 m/s. When the wind speed is between 4 m/s and 10.1 m/s in this study, over-speed is able to reach the De-loaded operation and the pitch angle control does not need to be activated. Therefore the pitch angle is fixed at zero by locking ω_{ref} as a constant of 1.2 p.u. When the frequency drops, the rotor speed control will increase active power to force the wind turbine to decelerate (Figure6).

2) Mode 2: medium wind speed mode (10.1–12 m/s)

When the wind speed is between 10.1 and 12 m/s in this study, over-speed cannot only provide the de-loaded operation because of the rotor speed upper limit. Thus, the regulation of pitch angle needs to be activated for assistance (Figure6).

In this study a pitch angle control scheme with variable ω_{ref} is proposed that ω_{ref} is calculated by (4).

3) Mode 3: high wind speed mode (>12 m/s)

When the wind speed is more than 12 m/s in this study, over-speed is impossible because the MPPT speed has been over 1.2 p.u. and the pitch angle control is activated. Therefore the rotor speed is fixed at 1.2 p.u. and the active power is initially set at 0.9 p.u. by the pitch angle controller. When the frequency drops, an active power increment is created by the decrease of pitch angle (Figure6).

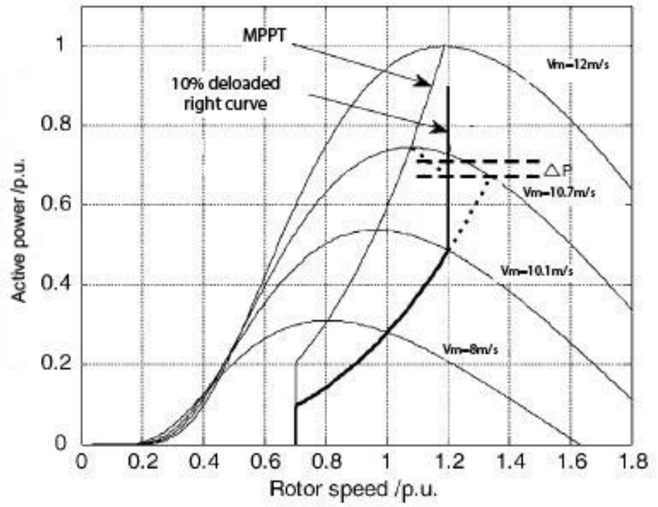


Figure 6. 10% de-loaded curve considering the rotor speed Limitation

III. The proposed combined control to improve frequency response

The proposed combined control includes simultaneous application of inertia controller and droop controller to improve the frequency response at the time of disturbance (frequency drop). Inertia control parameter value is used at the proposed pitch angle reference speed calculation. So a combination of inertia and pitch angle controllers in this simulation is applied.

In order to have more effect of this controller, the inertia controller and droop constant are supposed ($k_{\mathrm{inertia}} = 2 * 5.04$) and ($k_{droop} = 1/0.05$) respectively [13].

Choosing from non-control mode or combined control mode is possible by determining the values of coefficients of inertia and droop control.

IV. Test system

Studied systems, is simulated in MATLAB Simulink. This model includes a wind farm, three synchronous generator (900 MW) and a 160 MW load that is added at 30rd second as disturbance (Figure 7).

Nominal frequency is 60 Hz and variable speed wind turbines is operated in 90 per cent of optimal power, in other words, de-loading is considered10 percent.

The following three cases are studied in simulation.

Case 1: The wind speed is 8 m/s (within the low wind speed region).

Case 2: The wind speed is 11 m/s (within the medium wind speed region).

Case 3: The wind speed is 14 m/s (within the high wind speed region).

Simulation parameters are given in the table1.

Table1. Simulation parameters

Value	variable	value	Variable	value	variable
60 Hz	Frequency system	311*1.5MW	P_g(wind farm power)	35m	) blade radius(R
900MW	Synchronous generator	12m/s	Rated wind speed	1.225	ρ (air density)
160MW	load	27 deg	maximum pitch angle	8.1	λ_{opt}(tip –speed ratio)
		10 deg/s	pitch angle change rate limit	0.59	C_{Pmax}

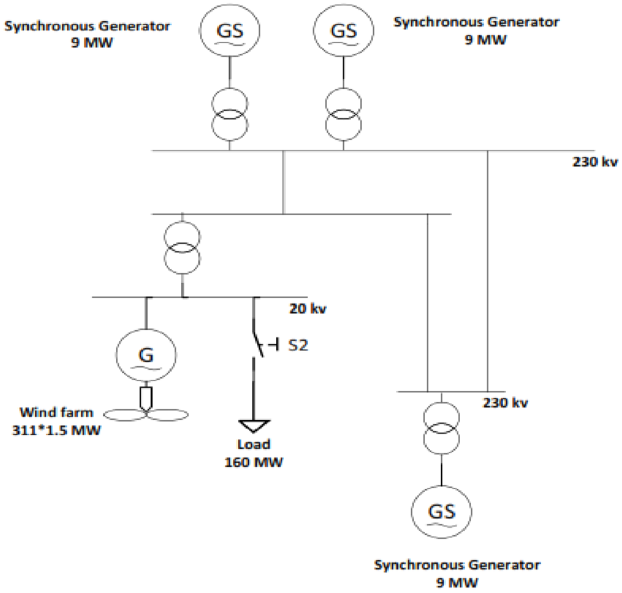


Figure 7. Power system model

V. Discussion and test result

Simulation outputs are analyzed and presented in four physical variables of system frequency, output active power, wind turbine rotor speed and pitch angle for the three wind speed mode. Figure9-11 compares three kinds of simulation curves that represent, for the conditions of combined control with the dashed line, only inertial control with the dotted line and no control with the solid line.

As the figure 9, 10 and 11 shows, drop in frequency happens at the third second due to disturbance event (load is connected). When the inertial controller is used, the kinetic energy is transiently released through rotor speed reduction and active power increased (see the dotted lines in Figs. 9d, 10d and 11d and 9b,10b and 11b respectively). Consequently, the frequency nadir point is clearly raised (dotted line in Figure 9a, 10a and 11a) and the frequency change rate is not as distinct as no control condition. The wind turbine is operated at an over-speed point and the active power is always increased by decreasing the rotor speed (see the dotted line in Figure 9d).

In case 1, the pitch angle control is deactivated as shown in Figure 9c because the rotor speed control could provide the frequency support for the system.

The simulations in cases 2 and 3 has similar results. With the combined control, the dashed line in Figure 10c shows that the pitch angle control is activated because only rotor speed control can't provide the reserve margin in the case 2. The active power output response to the frequency events (see the dashed line in Figure 10b) through reducing the pitch angle and rotor speed (see the dashed lines in Figs. 10c and d, respectively).

Figure 11d shows that the rotor speed has to be fixed at the maximum value in steady state because a wind turbine is not able for working at over-speed in the high wind speed case. The pitch angle control completes the steady-state frequency regulations (see the solid line in Figure 11c).

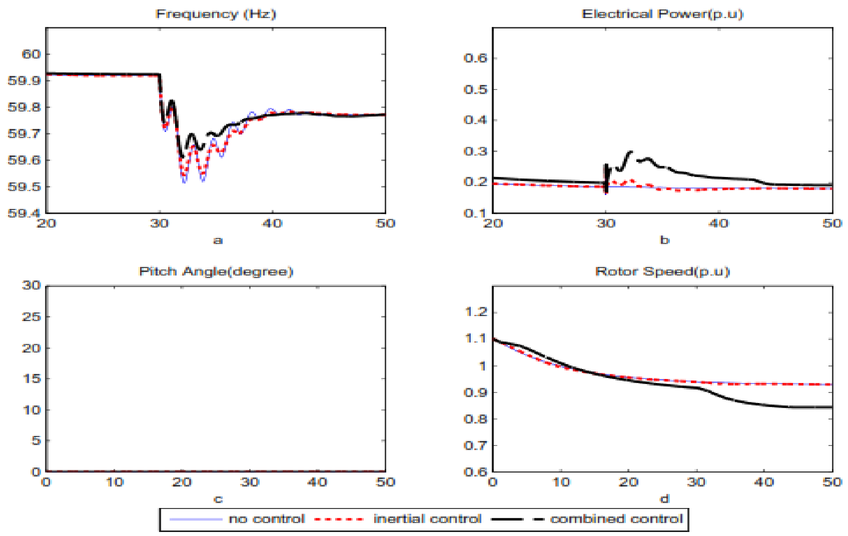


Figure 8. comparison of the parameters of frequency, power, pitch angle and rotor speed in three modes of no control, inertial control and combined control in case1

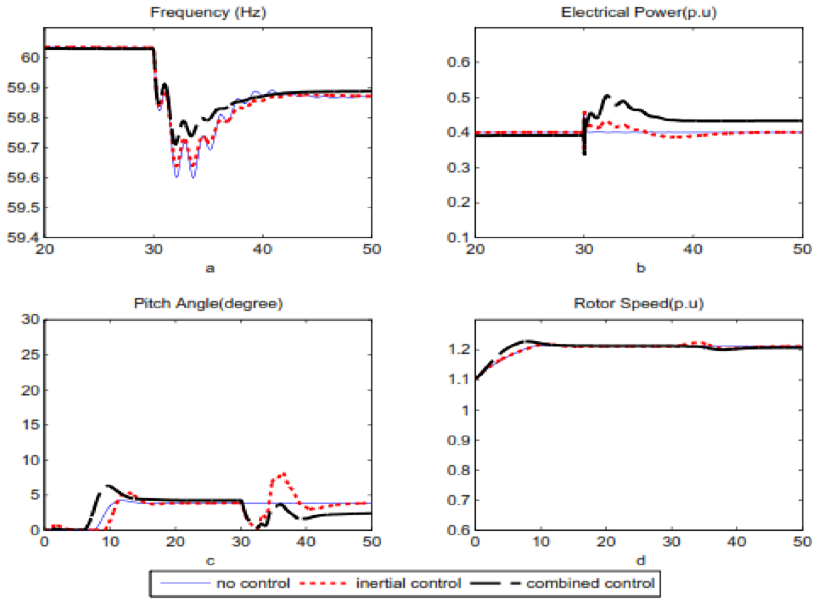


Figure 10. comparison of the parameters of frequency, power, pitch angle and rotor speed in three modes of no control, inertial control and combined control in case2

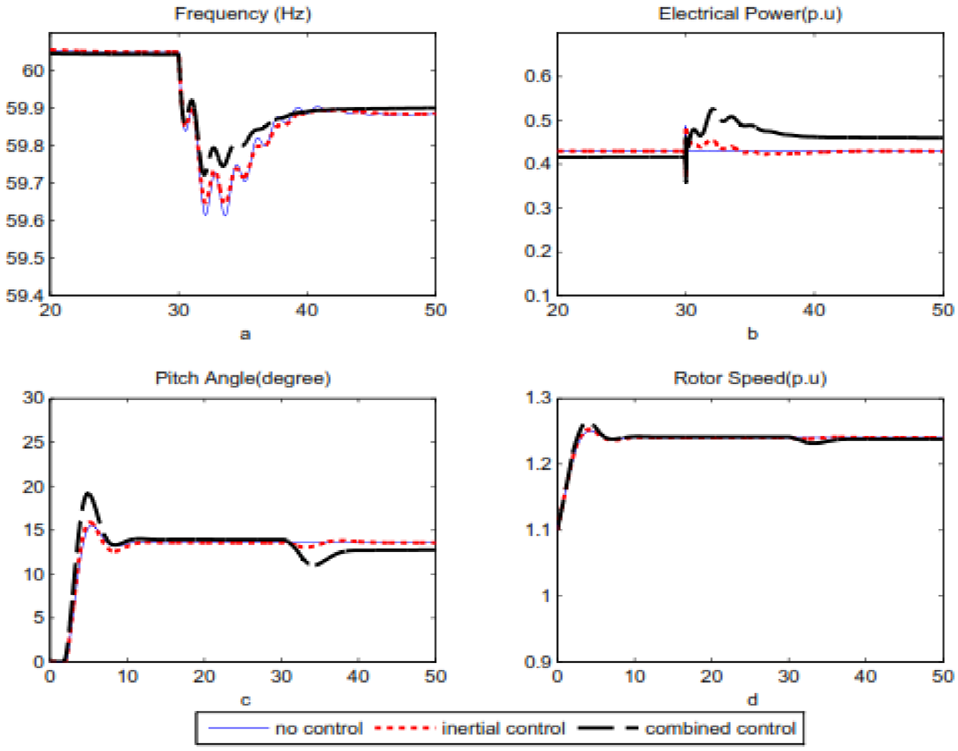


Figure 11. comparison of the parameters of frequency, power, pitch angle and rotor speed in three modes of no control, inertial control and combined control in case3

In the no control mode, frequency nadir is 59.61 Hz. Hz. If the inertial controller is used, frequency nadir will be 59.64 Hz (Figure10a.) and ROCOF is also less (Figure12).

However, the steady-state frequency is not improved (see the dotted line in Figure 9a, 10a and 11a) as no extra power reserves are put into use. But increases the transient frequency nadir.

Combined control improves frequency response (see the dashed lines in Figure 9a, 10a and 11a) and ROCOF (see the dashed lines in Figure 12).

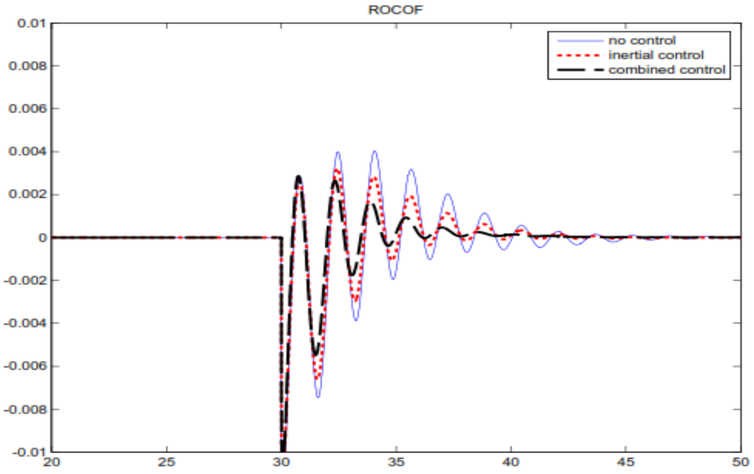


Figure 12. ROCOF comparison in three modes of no control, inertial control, and combined control

CONCLUSIONS

This study presents a novel control strategy through combining inertial and de-loading controls to allow DFIG-based wind turbines participating in primary frequency control.

The proposed combined frequency control strategy is generally suitable for all time scales. During transient, inertia controller helps to reduce the maximum frequency change rate and increases the transient frequency nadir.

In steady state, coordinated de-loading controls releases the reserved power to regulation the long-term frequency.

The DFIG can be controlled in three operating modes: (a) the low wind speed region (cut-in speed ─10.1 m/s), where de-loading is achieved through rotational speed increase; (b) the medium wind speed region (10.1─12 m/s), where a coordinated use of speed control and pitching is required; (c) the high wind speed region (cut-out speed ─12 m/s), where speed control essentially degenerates into pitching.

To analyze the impact of the proposed combined controller on frequency response, results in three modes of no control, with inertial control and proposed combined control, in MATLAB/SIMULINK, is checked out and analyzed.

The numerical simulations demonstrate that the combined control enhances the frequency regulation capability and improves the frequency response.

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