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RESEARCH ARTICLE

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Dynamic contribution of variable-speed wind energy conversion system in system frequency regulation

Abstract Frequency regulation in a generation mix having large wind power penetration is a critical issue, as wind units isolate from the grid during disturbances with advanced power electronics controllers and reduce equivalent system inertia. Thus, it is important that wind turbines also contribute to system frequency control. This paper examines the dynamic contribution of doubly fed induction generator (DFIG)-based wind turbine in system frequency regulation. The modified inertial support scheme is proposed which helps the DFIG to provide the short term transient active power support to the grid during transients and arrests the fall in frequency. The frequency deviation is considered by the controller to provide the inertial control. An additional reference power output is used which helps the DFIG to release kinetic energy stored in rotating masses of the turbine. The optimal speed control parameters have been used for the DFIG to increases its participation in frequency control. The simulations carried out in a two-area interconnected power system demonstrate the contribution of the DFIG in load frequency control.

Keywords doubly fed induction generator (DFIG), load frequency control, inertial control, wind energy conversion system (WECS)

1 Introduction

With the inclusion of large wind sources in the system, the conventional power sources will retire and there can be insufficient kinetic energy from the power plants to support the system frequency. The decrease in the number of synchronous units in operation may reduce system inertia and as a result the system's robustness regarding disturbances. Hence, as the wind penetration level rises, it is essential to explore the possibility of doubly fed induction generator (DFIG)-based wind turbine for frequency control along with conventional generators. The inertial and dynamic characteristics of wind generators differ from the conventional generators. The kinetic energy of conventional generators will no longer be available to support the system frequency in the event of any contingency. Such problems become delicate in isolated systems and needs investigations regarding potential of wind parks to participate effectively in primary frequency regulation. If installed wind capacity can contribute some inertia, the adverse effects of contingency can be reduced [1,2].

The technological advancements have made it possible for wind generators to participate in frequency control. It increases the robustness of operation and makes wind power penetration safer. In the case of DFIG, the inertia of the turbine is effectively decoupled from the system thus, preventing the generators from responding to system frequency changes. The power electronic controller controls the performance and acts as an interface between the machine and the grid. This behavior of DFIGs when operating in large numbers is not desirable, as the frequency of the system will change rapidly due to disturbance with lower inertia. Few methods are reported in literature on how variable speed wind turbine (VSWT) can participate effectively in system frequency regulation [3–5]. The first method is based on inertial control; the second is power reserve control method (pitch control and speed control) and the third is control by communication method. Inertial control is provided by the DFIG through a supplementary inertia control loop [6]. This additional inertia control loop is sensitive to system frequency and it releases the kinetic energy from rotating masses of the DFIG-based wind turbines. The DFIGs react instantly to

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disturbances and primary frequency control is applied by injecting active power during frequency excursion. The additional amount of power supplied by the wind generator to the grid is proportional to the derivative of system frequency. The capability of the DFIG in frequency regulation is exploited through a combination of control of static converters and pitch control, adjusting the rotor speed and the active power according to the deloaded optimum power extraction curve [7]. Dynamic participation of the DFIG in frequency control is analyzed by a frequency control support function which responds proportionally to frequency deviation and the kinetic energy of turbine blades is used to improve frequency [8,9]. The contribution of the DFIG in frequency regulation is also analyzed by governor setting and system inertial response. A novel control algorithm is proposed for extracting maximum energy from the turbine in a stable manner [10].

Different types of controllers are used to maintain the power system in a normal state of operation. These controllers for automatic generation control (AGC) are proportional and integral (PI), proportional-integral-derivative (PID), and optimal controllers. Among other controllers fuzzy-based controller is also very efficient in system frequency regulation. Fuzzy controller is used to provide ancillary services through price-based and bilateral contract mechanisms in a competitive way in a market structure [11]. A fuzzy-based automatic generation controller with flexible alternating current transmission (FACT) device is also proposed for frequency control in open access market scenario. The phase angle control of TCPS is used to stabilize the system frequency and tie-line power oscillations along with fuzzy controller [12]. The gain of the controllers can be set to control fast transient recovery and low overshoot in the dynamic response of the system. The gain setting of these controllers is done by approaches like integral square error (ISE) and other optimization methods like particle swarm optimization. PI controllers improve steady state error with little or no overshoot.

Wind generators generally do not contribute to system frequency regulation, i.e., they do not increase or decrease the generation during frequency excursions. The objective of this paper is to analyze the load frequency control problem of a two-area interconnected system when the DFIG- based wind turbines are connected to both areas and are contributing to system inertia. Based on frequency deviation signal, the DFIG injects the electrical power and provides inertial support to the system. The energy required is taken from the kinetic energy stored in rotating masses of wind turbines, causing variations in rotor speed. Since the kinetic energy stored in rotating masses is limited, the wind units contribute to system inertia only for short periods of time. Thus, wind generators only provide primary frequency control while the final generation has to be taken over by the conventional plants. This can be really helpful as the conventional units respond slowly after disturbance and wind units can arrest initial fall in frequency. Different wind penetration levels were used and frequency responses for load perturbation of 2% have been presented by obtaining optimized speed control parameters for the DFIG. The simulations were conducted using SIMULINK model in MATLAB.

2 VSWT for frequency control

The fixed-speed turbines are prevented to supply their maximum available power in normal situations so as to maintain a reserve margin that can be utilized for frequency control. However, with VSWT extracting the kinetic energy stored in the mechanical system of wind turbines is easier with modern power electronic control. In literature there are different methods to use VSWT effectively in system frequency regulation [5]. These are inertial control, pitch control and speed control.

2.1 Inertial control

The inertial control of VSWT to support system inertia is applied by two different methods. One tries to create momentarily wind turbine inertial response and the other utilizes the droop characteristics. The first control makes wind turbine to respond frequency disturbances and amount of power supplied by the wind turbine is proportional to the derivative of frequency [6]. The second control strategy is similar to primary frequency control of conventional plants. The amount of power supplied by the wind turbine is proportional to the difference between the measured and the nominal frequency.

The inertial control scheme, as depicted in Fig. 1, is responsible for sending additional power regulation signal P_{ref} to the rotor side converter. During load perturbation, in addition to the conventional plants, the wind unit inertial control loop also sends additional active power to VSWT active power reference P_{ref} and quickly changes its output active power to contribute in frequency restoration process. Thus, wind unit behaves like a synchronous generator and increases the system inertia virtually.

2.2 Pitch control

Pitch angle control in wind turbine is designed much similar to the governor control of synchronous machine to make it have long-term frequency regulation capabilities. The pitch control limits the active power to a limit less than its normal output. As frequency changes, the reserve power is delivered by decreasing the pitch angle, which helps the wind turbine extract more mechanical power from wind flow. To generate the optimum power, the turbine blades have to adjust accordingly. This adjustment comes from turning the blades around their longitudinal axis (to pitch).

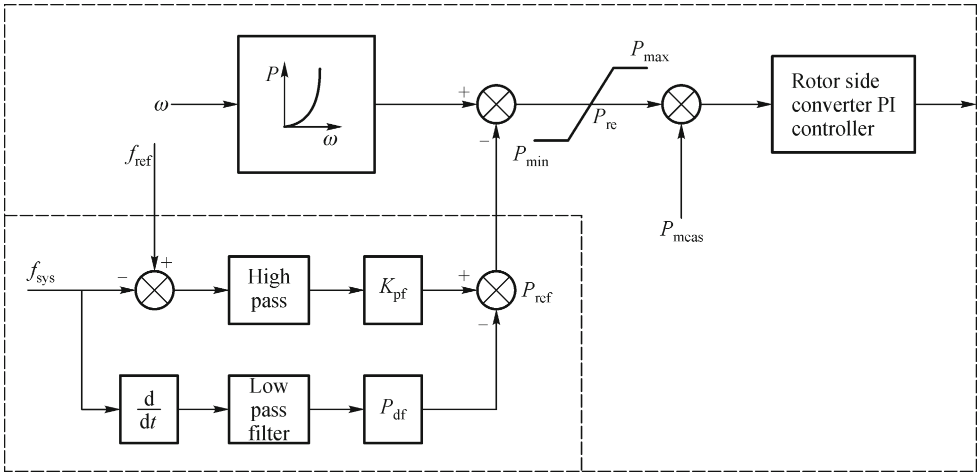

Fig. 1 Inertial control scheme

When the wind speed decreases, the blade pitch is adjusted such that it exposes more surface area to the wind. Conversely, when wind speed increases, the blade pitch is adjusted such that it exposes less surface area to the wind. It should be noted that for any given wind speed there is an optimal turbine rotational speed which has to be maintained during deloading through pitching.

2.3 Speed control

The wind turbine can be deloaded if it is made to operate at increased speed and a power rotational speed setting different from the optimal value is selected. The wind turbine speed is decreased to increase the turbine output and vice-versa. The kinetic energy stored is transferred to or from the grid.

Figure 2 shows the variation of maximum power available with wind speed. The optimal power can be generated for a particular wind speed. However, the wind turbine is made to operate along 95% curve, which forces it to generate power less than the maximum power available. Thus, there remains some reserve available for primary frequency regulation. The adoption of this power reference curve allows the increase in the active power generated by the wind turbine when frequency decreases due to load perturbation.

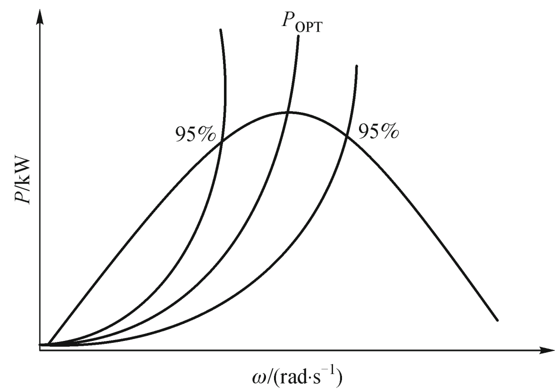

Fig. 2 *P* vs. *ω* curve for maximum power available

3 Simulation models

Figure 3 illustrates the linearized model of two-area interconnected power system for load frequency control. The control area is comprised of non-reheat type conventional generators along with non-conventional (DFIG-based) wind turbine generators connected to both of the areas contributing to frequency regulation. The model simulates frequency regulation after a disturbance and includes conventional system parameters such as damping factor (D), the droop (R), the inertia H, governor time constants T_h and T_t of the system equivalent (governor and turbine) unit. T_P and K_P are power system time constant and power system gain respectively. The ΔP_h is the incremental hydraulic valve position change. The turbine has ΔP_g as the output from which the incremental power demand ΔP_D is subtracted, along with total active power interchanged (ΔP_{12}) with neighbor systems while the power supplied by non-conventional source ΔP_{NC} is added to the system as indicated in Eq. (1):

$$\Delta P_g + \Delta P_{NC} - \Delta P_{12} - \Delta P_D = \Delta P_f, \quad (1)$$

where

$$T_P = \frac{2H}{fD}, \quad (2)$$

$$K_P = \frac{1}{D}. \quad (3)$$

The ΔP_{ref} stands for the secondary control or AGC power reference which is provided by the PI controller.

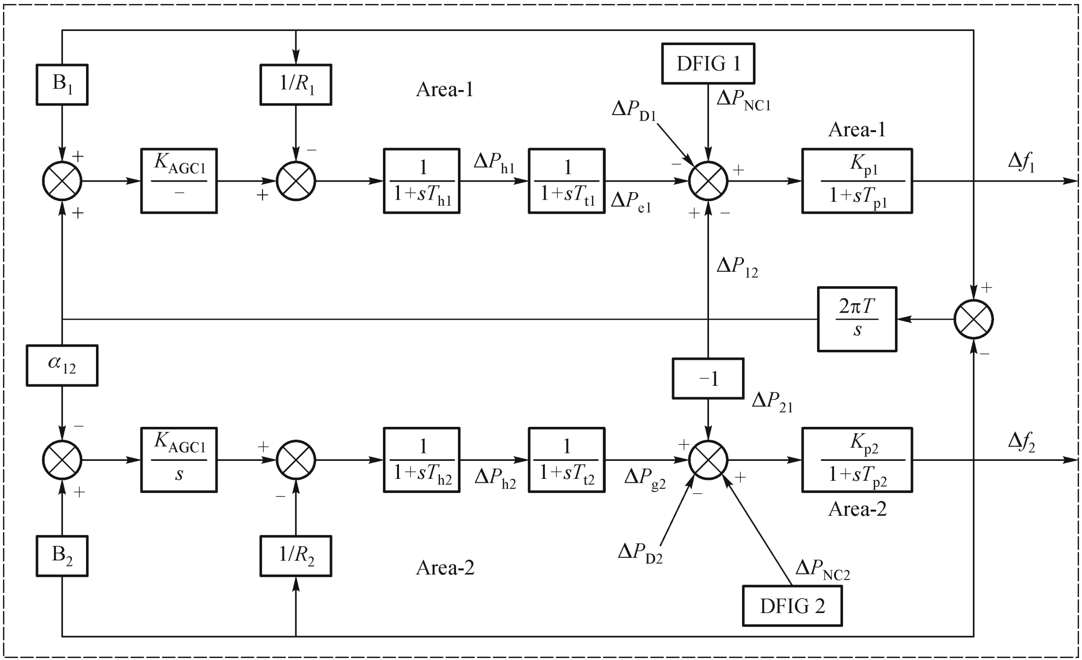

Fig. 3 Linearized model of two-area interconnected power system

The dynamic model adopted for study of frequency regulation with DFIG-based wind generator, as demonstrated in Fig. 4, has the essence of emulation control as given in Refs. [13,14]. In emulation control of the DFIG, an additional control signal helps to adapt the power set points $\Delta P_{\mathrm{f}}^{*}$ as a function of deviation and rate of change of frequency. The controllers try to keep the turbine at its optimal speed in order to produce the maximum power. The controller provides a power set point ΔP_{ω}^{*} that is based on measured speed and measured electrical power.

The support to frequency exceeds certain limits by adding this signal to the torque equation to set the torque demand. As the system frequency drops, the set point torque is increased and the rotor slows down and kinetic energy is released. The ΔP_{NC} has two components; $\Delta P_{\mathrm{f}}^{*}$ the additional reference point based on frequency change, and ΔP_{ω}^{*} which is based on optimum turbine speed as a function of wind speed, as is given by

$$\Delta P_{\mathrm{f}}^{*} = -K_{\mathrm{df}}\frac{\mathrm{d}f}{\mathrm{d}t} - K_{\mathrm{pf}}\Delta f, \tag{4}$$

$$\Delta P_{\omega}^{*} = -K_{\mathrm{wp}}(\omega^{*} - \omega) + K_{\mathrm{wi}}\int(\omega^{*} - \omega)\mathrm{d}t, \tag{5}$$

$$\Delta P_{\mathrm{NC}} = \Delta P_{\mathrm{f}}^{*} + \Delta P_{\omega}^{*}, \tag{6}$$

where K_{wp} and K_{wi} are constants of the PI controller, which provides fast speed recovery and transient speed variation, which helps the non conventional generators to supply the required active power to reduce deviations. The contribution of the DFIG towards system inertia is given by

$$\begin{aligned}\frac{2H}{f}\frac{\mathrm{d}\Delta f}{\mathrm{d}t} &= \Delta P_{\mathrm{f}} - D\Delta_{\mathrm{f}} \\ &= \Delta P_{\mathrm{g}} + \Delta P_{\mathrm{NC}} - \Delta P_{12} - \Delta PD - D\Delta f,\end{aligned} \tag{7}$$

$$\begin{aligned}&\underbrace{\left(\frac{2H}{f} + K_{\mathrm{df}}\right)}_{2H^{*}}\frac{\mathrm{d}\Delta f}{\mathrm{d}t} \\ &= \Delta P_{\mathrm{f}} - D\Delta_{\mathrm{f}} \\ &= \Delta P_{\mathrm{g}} + \Delta P_{\mathrm{NC}} - \Delta P_{12} - \Delta PD - \underbrace{(K_{\mathrm{pf}} + D)}_{D^{*}}\Delta f.\end{aligned} \tag{8}$$

The swing Eq. (7) gives an idea about the contribution of the DFIG towards system inertia. It has an additional reference power setting which is built based on the change in frequency using a washout filter with time constant T_{w}, that relies on a conventional primary regulation performance in a transient.

$$\Delta P_{\mathrm{f}}^{*} = \frac{1}{R}(\Delta X_2), \tag{9}$$

where, R is the droop constant as used conventionally and ΔX_2 is the frequency change measured where the wind turbine is connected to the network.

The DFIG responds to frequency deviations during transients by using their stored kinetic energy, and cannot act in a permanent system frequency deviation. For this reason, the frequency term (ΔX_2) used in Eq. (9) is the result of a washout filter, as displayed in Fig. 4. In this

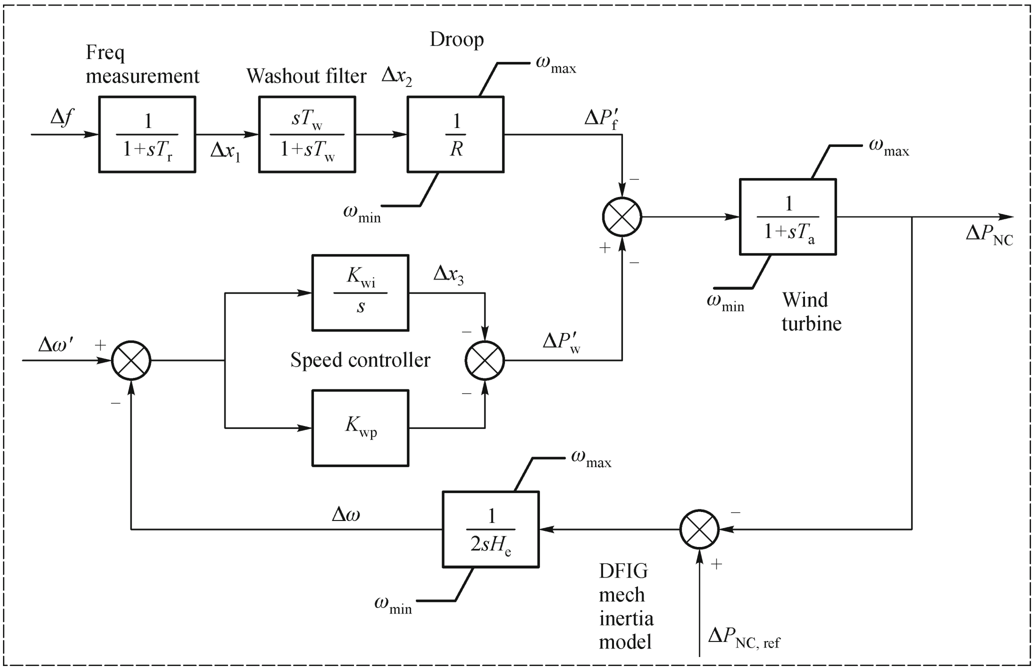

Fig. 4 DFIG-based wind turbine control based on frequency change

approach wind energy conversion system (WECS) inertia contributes to that of the rest of the system. The controller proposed makes use of frequency deviations instead of derivative of frequency as in the control law to provide fast active power injection control. The active power injected by the wind turbine is ΔP_{NC}. The power injected is compared with ΔP_{NCref} so as to obtain the maximum power output, which is obtained by maintaining reference rotor speed where maximum power is obtained.

4 Simulations and results

Simulations have been conducted in a two-area system to investigate the role of the DFIG in system frequency control. The parameters of the DFIG-based wind turbine are given in Table 1. The interaction between the DFIG-based wind turbine and the traditional plants has been investigated for a load perturbation of 2% for different level of wind penetration. The level of wind penetration is defined as

$$W_s = \frac{\text{Wind generation}}{\text{Total generation}}. \tag{10}$$

The wind turbines respond very quickly to the system disturbance and release the kinetic energy stored in their masses to support system inertia. As the DFIG acts swiftly to disturbance, its fast action can delay the response of the conventional generators. Coordination is needed between the response changes (available during transients only) of the DFIG and the response of the conventional units in restoring the frequency. The response of the conventional generators is provided by the PI controllers. To enhance the participation of the DFIG in frequency control in response to system disturbances, optimal values of the speed control parameters (K_{wp} and K_{wi}) of the DFIG-based wind turbine have been obtained. The ISE technique is used for obtaining the optimum values of K_{wp} and K_{wi} to minimize the objective function defined as “performance index J”:

$$J = \sum[\Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie}^2]\Delta T, \tag{11}$$

where ΔT is a given time interval for taking samples, Δf_i is discrete value of incremental change in frequency for the ith area and ΔP_{tie} is value of incremental change in tie-line power. The sample values are obtained from their respective plots derived through transfer function analysis. The optimal values of the DFIG speed controller parameters are obtained by searching for the minimum value of J as listed in Table 2.

Different levels of wind penetration were applied and the results have been shown for 10 % wind penetration level. During simulation it has been assumed that the wind speed remains constant and the DFIG-based wind turbines are in their optimal mechanical speed with the maximum speed obtainable from the wind. In Fig. 5, the frequency responses of the two areas are presented for the cases where the DFIG is participating in frequency control and not participating in frequency control for a load perturbation of 2% in area-1 at 0.1 s. The results show that the frequency response of both areas are better in terms of lesser settling time and smaller lower peak excursion when the DFIG is participating in frequency control. However,

Table 1 Model constants used for simulation

Description	Area-1		Area-2	
	Parameter	Value	Parameter	Value
Equivalent wind turbine inertia	H_{e1}	1.5 pu·MW·s	H_{e2}	1.5 pu·MW·s
AGC integral control gain	K_{agc1}	0.05	K_{agc2}	0.05
Power system gain	K_{p1}	50 Hz/pu	K_{p2}	60 Hz/pu
DFIG integral controller gain	K_{wi1}	0.1	K_{wi2}	0.1
DFIG proportional speed controller gain	K_{wp1}	1.23	K_{wp2}	1.58
Regulation droop	R_1	3	R_2	3
Tie line synchronizing coefficient	$T°$	0.07 pu·MW/Hz	$T°$	0.07 pu·MW/Hz
DFIG turbine time constant	T_{a1}	0.2 s	T_{a2}	0.2 s
Conventional generation governor time constant	T_{h1}	0.1 s	T_{h2}	0.1 s
Power system time constant	T_{p1}	10 s	T_{p2}	10 s
Transducer time constant	T_{r1}	15 s	T_{r2}	15 s
Conventional generation turbine time constant	T_{t1}	1 s	T_{t2}	1 s
Washout filter time constant for DFIG	T_{w1}	6 s	T_{w2}	6 s

Table 2 Optimal parameters of the controllers for 10% wind penetration

Area-1		Area-2	
K_{wi1}	K_{wp1}	K_{wi2}	K_{wp2}
0.1	1.23	0.1	1.58

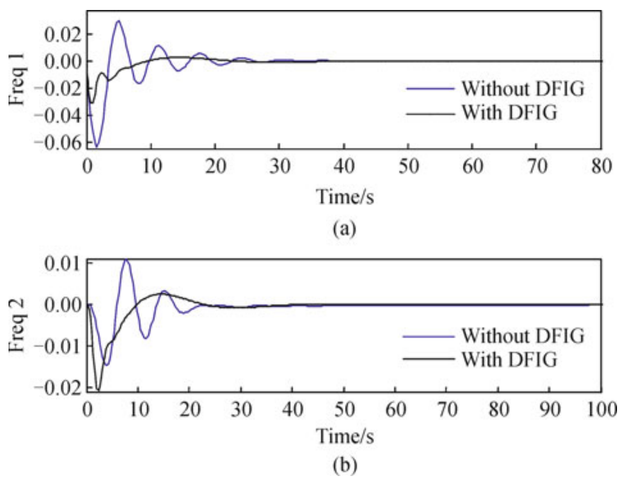

Fig. 5 Area frequency responses with and without DFIG

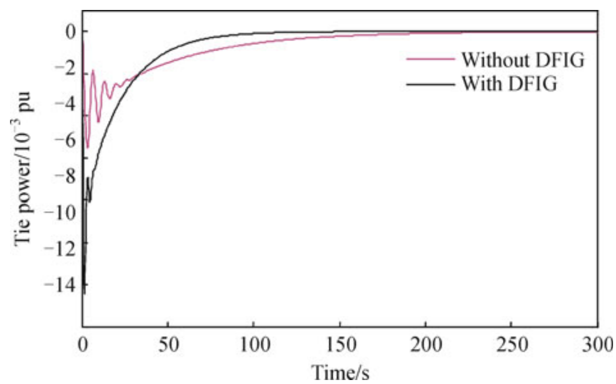

Fig. 6 Tie-line power

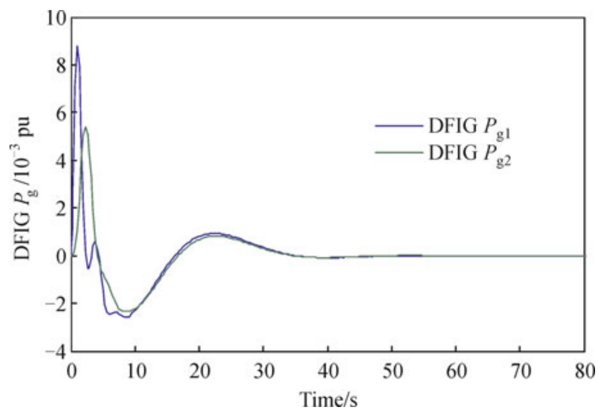

Fig. 7 Generation response from the DFIGs of two areas

without the DFIG the overshoots and undershoots are higher and settling time also is larger. The undershoot in area-1 where load perturbation takes place is higher as compared to area-2.

Figure 6 shows power increment changes for tie-line for 10% wind penetration. Though the increment is slightly large for the system with the DFIG but the response settle faster than the system without DFIG operation. The DFIG responds quickly to provide support to system inertia by releasing their kinetic energy for the initial few seconds only. Figure 7 presents the generation response of the DFIG in area-1 and 2, which is higher for the DFIG in area-1 where load has changed.

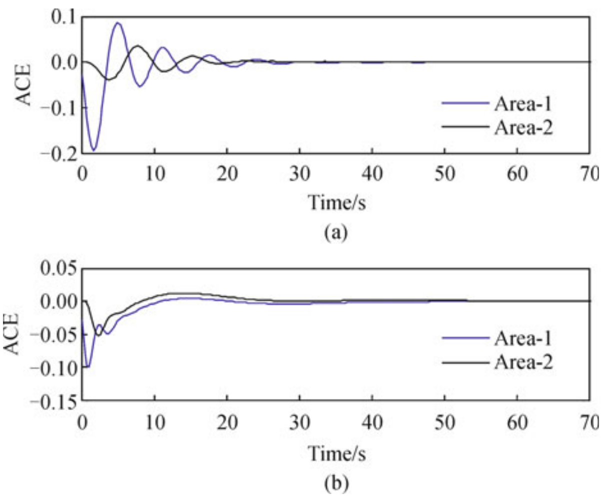

Fig. 8 ACEs of two areas. (a) Without DFIG; (b) with DFIG

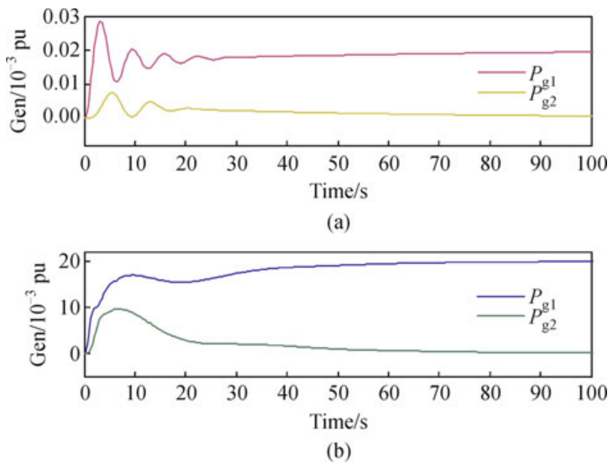

Fig. 9 Generation response of the conventional units. (a) Without DFIG; (b) with DFIG

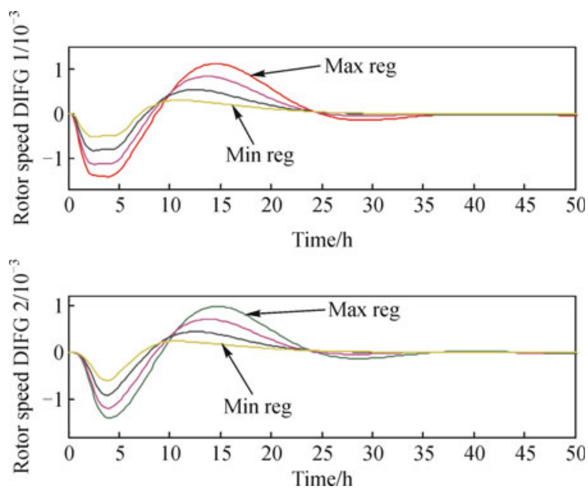

Fig. 10 Speed variations of DFIG-based wind turbines following a load change of 2% in area-1 under different regulation support

Figures 8(a) and 8(b) depict the area control errors (ACEs) for area-1 and 2 following a step load perturbation in area-1. It is observed that the errors when the DFIG is participating in frequency control are much less. Overshoot are smaller. However, the settling time rises due to wind turbine deviation from its optimal speed.

The DFIG provides system frequency support in initial intervals of disturbance which delays the response of conventional generators. As the inertia of conventional units is large, they change their generation afterward. Figure 9 presents the generation response of the conventional units with and without the DFIG participating in frequency regulation. The peak excursions are higher in the system without the DFIG but much lower when the DFIG provides frequency support. As wind units provide support only during transients, the conventional units increase their generation. Conventional unit 1 increases the generation higher than unit 2 as fault is in area-1. It can be seen that except the peak excursion in the initial few seconds, the generation change in unit 1 is similar with and without the DFIG support, which confirms the participation of the DFIG in frequency support during transients only.

The DFIG-based wind units provide frequency support, by releasing the kinetic energy stored in the rotor and blades of the wind turbine. This is done by lowering the speed momentarily. The droop loop (regulation R) is used to produce a change in active power injection by the wind turbine which is proportional to the difference between the measured and the nominal system frequency. The energy needed is taken from the kinetic energy stored in rotating masses, leading to variations of the rotor speed. The regulation required to extract higher active power from the wind unit is also higher. The rotor speed responses of the DFIGs are exhibited in Fig. 10 for optimally tuned parameters with different regulation control.

Two load perturbations of 1% and 2% respectively were applied in area-1 at time zero and twenty second on the system model. The frequency responses of two areas settle smoothly and peak overshoots are less in the system where the DFIGs are contributing to system inertia, as seen in Fig. 11.

The simulations were also performed for different wind penetration level for a load perturbation of 2% in area-1 and frequency response was plotted for each case. Figures 12 and 13 show the frequency response in area-1 and area-2 respectively for different wind penetration level. It can be observed that for different wind penetration level, frequency responses have almost equal undershoot (US), however the overshoots (OS) decrease with the increase in wind penetration level, thus confirms the participation of wind generator in frequency control. Table 3 shows the US

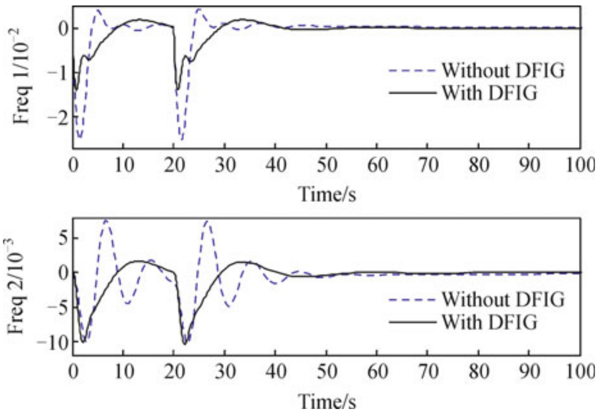

Fig. 11 Frequency response for load perturbation of 1% and 2% at time zero and 20 s respectively

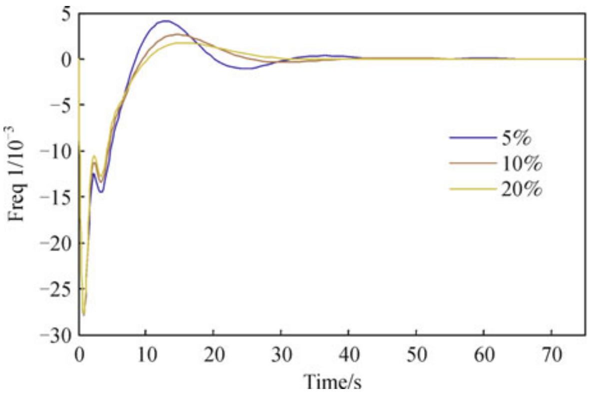

Fig. 12 Frequency response of area-1 for different penetration level

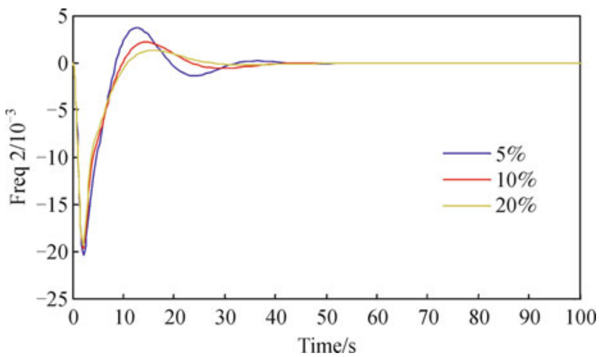

Fig. 13 Frequency response of area-2 for different penetration level

and OS of frequency response for different wind penetration level. The settling time of frequency responses increases for higher penetration level which is due to the fact that the DFIG has to reduce the mechanical speed, which prolongs the settling time. Simulation results show the improvement in frequency response with active power

Table 3 US and OS of frequency responses for varying wind penetration level.

		5%	10%	20%
Freq_1	US	−0.0276	−0.0276	−0.0275
	OS	0.004125	0.00263	0.00182
Freq_2	US	−0.0203	−0.01969	−0.01941
	OS	0.0037	0.00217	0.00131

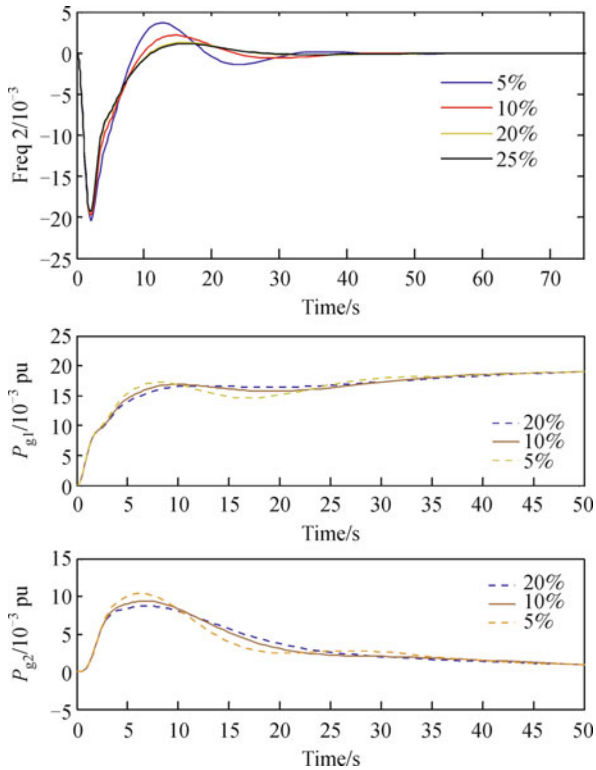

Fig. 14 Generation response of conventional generators at different wind penetration level

support from DFIG, which confirms the participation of the DFIG in frequency control. The higher wind penetration can improve the frequency profile as compared to no wind support.

The capabilities of fast response of wind units can be used to arrest the initial drop in the frequency. Since conventional units take some time to respond to any change (generation loss, load change etc.), the DFIG along with conventional unit can be used effectively in frequency regulation. Figure 14 shows the generation response of the conventional units under different wind penetration level. As the wind units provide support only during transients, the final generation is taken over by the conventional units by increasing their generation. The conventional unit 1 increases a higher generation than unit 2 as fault is in area-1. As the wind units only act during transients, the response of the conventional units also get delayed, hence a proper coordination between the wind unit and the conventional generators through communication system should be established to regulate the frequency effectively.

5 Conclusions

This paper examines the dynamic contribution of the DFIG-based wind turbine towards load frequency control. The modified inertial control scheme helps the DFIG to provide support to the system inertia during transients and arrests the fall in frequency. The DFIG releases the kinetic energy stored in its rotating masses to provide quick frequency support. The optimized controllers' parameters have been used to obtain the response. The DFIG responds more quickly to any disturbance as compared to the conventional generators, which sometimes delay the reaction time of the conventional generators after disturbance. However, the conventional generators finally respond with change in generation to settle the frequency deviation. The peak frequency excursions of the responses are reduced and settling time is also improved when the DFIG-based wind turbines participate in frequency regulation along with the conventional generators. The frequency responses of the two-area system, generation response of the conventional generators and tie-line fluctuations confirm the participation of the DFIG in frequency regulation. Thus, a good coordination between inertial support from the DFIG and the conventional generators can help the system to restore stable operation following any fluctuation.

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