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On Contribution of DFIG Wind Turbines in the Secondary Frequency Control

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Abstract— **Nowadays power systems experience integration of wind energy in the world electric networks. New problems and challenges are created with high penetration of wind power. One of new problems is the frequency control. Double fed induction generators (DFIGs) are most common type of wind turbines in the modern power systems. Naturally, the DFIGs do not participate in the frequency control task; however they could be equipped with supplementary control loop. For the purpose of inertial response and primary frequency control, necessary control loops have been already designed. In this paper, a supplementary control loop is proposed for secondary frequency control. This control loop uses a PI controller for restoration of frequency to the nominal value. To demonstrate the effectiveness of the proposal approach, it is examined on an updated IEEE nine-bus system.**

Keywords— ***Wind energy; inertial response; primary frequency control; secondary frequency control; supplementary control loop***

I. INTRODUCTION

Currently, the demand for electricity energy is increasing and the use of fossil-fueled and conventional generating units is not economic, and produces the greenhouse gases such as carbon dioxide. Approving Kyoto Protocol in 1997 [1], the use of renewable energy for reduction of carbon dioxide and other greenhouse gases have been started. In the last decade, wind energy has a substantial growth among renewable energy sources. This increase in the use of wind energy causes new problems and challenges in power systems. One of these challenges is the frequency regulation issue [2].

Nowadays, it is expected that wind turbines could be able to provide ancillary services (for example active power reserve) similar to conventional generating units. In general, wind turbine generators (WTGs) may be divided into two principal categories: fixed speed and variable speed [3]. The use of variable speed is more usual because of capability to generate maximum power in any speed, better quality of output power, capability of controlling active and reactive power. Inertial response, primary control and secondary control are important issues in frequency control.

In [3, 4, 5], it has been illustrated that since rotational speed of DFIG is not directly connected to the network, it naturally do not contribute in inertial response. In [3], the importance of inertial response in frequency regulation and security of system has been discussed and it is illustrated that by increasing in the number of DFIG in a power system instead of synchronous generators, the total inertia of the system will be reduced. This causes increase in the rates of change of frequency (ROCOF) and activates the load shedding in system and descending the security of the power system. In [5], it has been illustrated that maximum ROCOF is sensitive to the amount of installed wind capacity. Also the type of installed wind turbine technology has a little influence on the maximum ROCOF and it has been expressed that the amount of frequency nadir depends on the type of wind turbine technology. In [3, 5], it is shown that by adding a supplementary control loop the inertial response can be created in the DFIGs. In [6-9], contribution of the DFIG in primary frequency control is studied. For primary and secondary frequency controls, the DFIGs should reserve a part of their powers. Two ways are introduced for this propose:

a) De-loading of maximum power curve.

b) Increase of pitch angle at high wind speed for decreasing the wind energy.

The latter one is similar to the governor control in the conventional units. In [10], it is expressed that synchronous generators can use the droop characteristic for primary frequency control. In [6-9], it is illustrated that by another control loop, the DFIG can contribute satisfactorily in primary frequency control similar to the synchronous generator. In [11], it has been illustrated that contribution of wind turbines in frequency control depend on the response speed of synchronous generator controllers. For faster controllers, the inertia control seems to be slightly preferable. But the amount of power that is required to limit the frequency drop is smaller and consequently the mechanical and electrical stresses are lower.

Also the rate of increase of power dP/dt is slower, which will further reduce the mechanical stresses, especially for the shaft torque. In [7], an idea is introduced for the secondary frequency control without realization. In this paper, the mentioned idea is completed and is realized on the standard IEEE nine-bus system, and then the results for primary and secondary controls are compared. This paper is organized as follows: The DFIG wind turbine technology is introduced in section 2. An overview on inertial response and primary frequency control with the related loops is presented in Section 3. Section 4 introduces secondary control and a new supplementary control loop for the DFIG. In section 5, a case study is introduced. Results of simulation are presented in section 6, and finally conclusions are given in section 7.

II. DFIG WIND TURBINE MODEL

A DFIG unit includes a wind turbine, induction generator and back to back converter. Stator side of generator is directly connected to the network and the rotor side of induction generator is connected to the network through a back to back converter. Active power is always injected to the network from stator side but from rotor side depending on the rotor speed, active power can be injected to the network and can be absorbed from network. In general, the injected active and reactive power to the network through rotor side converter is controlled and stator side converter is used for the control of DC voltage bus. Fig. 1 shows the block diagram of the DFIG.

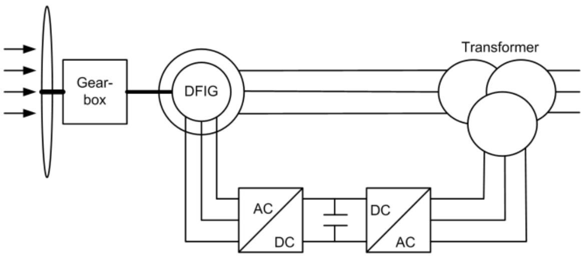

Fig. 1. Block diagram of the DFIG.

In this paper, the goal is active power control; therefore only the rotor side converter is expressed. Fig. 2 shows a control model for DFIG unit, but naturally a DFIG does not include three blocks shown in the figure i.e. block 1: inertial response (Δp_1), block 2: primary control (Δp_2) and block 3: secondary control (Δp_3). Each block adds an active power to the maximum power curve (or de-loading maximum power curve). First and second blocks have been introduced in the previous works. This paper is focused on the third block.

In Fig. 3, de-loading maximum power curve is shown for 20%. It is notable that for creation of reserve, we can use both side (right and left) of maximum power curve, but right side is better because in this case, the rotational speed as well as increases the kinetic energy for supporting of inertial response and primary frequency control. The protection system of the DFIG is activated when the rotational speed exceeds from its margin.

III. A REVIEW ON THE INERTIAL RESPONSE AND PRIMARY CONTROL

In this section, inertial and primary blocks shown in the Fig. 2 are explained.

A. Inertial response

For contribution of the DFIG in the total inertia of the system, a supplementary control loop has been introduced in [3, 5]. This control loop is shown in Fig. 4. The employed first order filter (Fig. 4) is used for reduction of frequency distortion. In this figure, f is the frequency of the system and H is inertia constant of the DFIG and Δp_1 is the additional power that is released from the kinetic energy stored in the blades of wind turbine, so that, this power is added to the power taken from the maximum power curve (or de-loading maximum power curve).

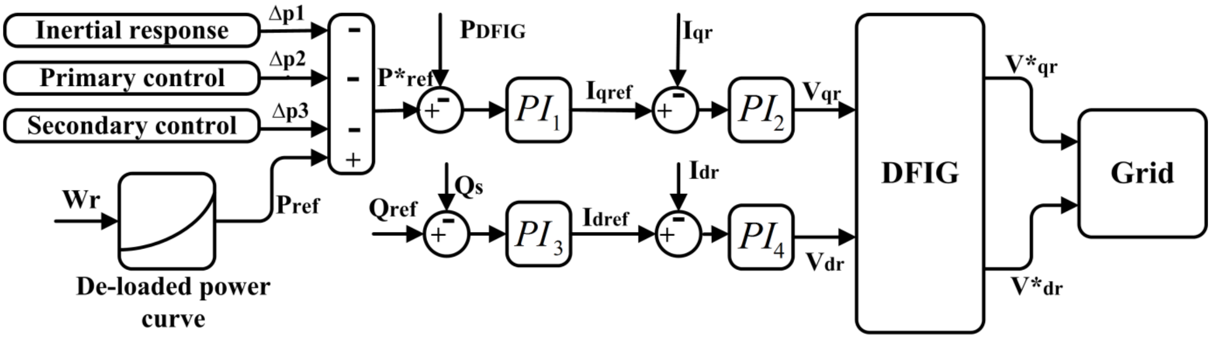

Fig. 2. Control structure for rotor side of DFIG

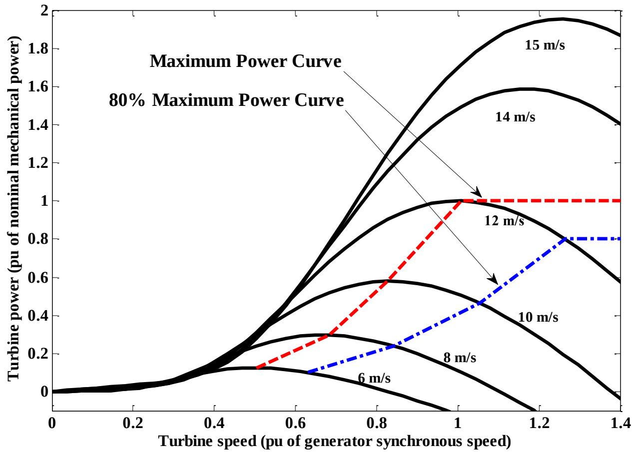

Fig. 3. De- loading power curve of DFIG

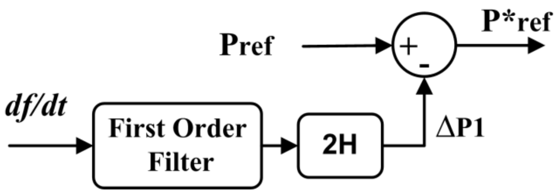

Fig. 4. Inertial response block

B. Primary frequency control

Similar to the synchronous generators, the DFIGs can use additional control loops for contribution in the primary control. In this loop, the frequency of system is compared with a nominal value and in accordance with the difference between these two signals, the active power reference value extracted from the de-loading maximum power curve will change. The related control block is shown in the Fig. 5. Similar to the synchronous generators, the DFIG uses a droop frequency characteristic which is shown in Fig. 6. The constant K_{pdf} is determined according to the droop characteristics. In this paper, when rotational speed exceeds from 1 pu, the protection system of the DFIG is activated and wind farm will be disconnected from the system. To avoid wind farm disconnection, the pitch angle controller is used to prevent increasing rotational speed. The control block for the pitch angle is shown in Fig. 7.

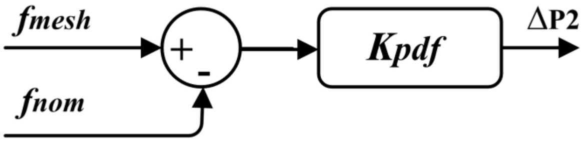

Fig. 5. Primary frequency control block.

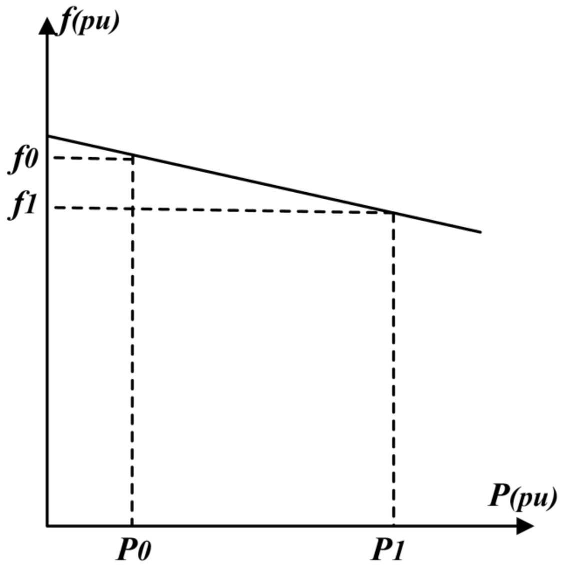

Fig. 6. DFIG droop characteristic

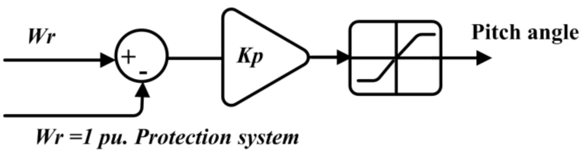

Fig. 7. Pitch angle controller block

C. Secondary frequency control

It is necessary to allocate a part of active power generating unit (spinning reserve) for contribution in the secondary control task. In this paper, the pitch angle and de-loading maximum power curve are used for creation of active power reserve. This section introduces a secondary control loop for restoration of frequency to its nominal value. In this loop, the frequency variation is used through a PI controller for changing active power reference value extracted from de-loading maximum power curve. Indeed, this control loop releases the reserve power of DFIG. If the contribution of the DFIG in the LFC to be necessary, the frequency variation should be replaced by area control error (ACE) signal. In Fig. 8, this control loop is shown.

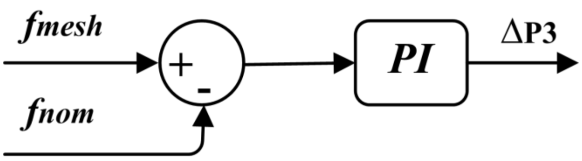

Fig. 8. Secondary frequency control block.

IV. CASE STUDY

In the present paper, some simulations were performed on the updated IEEE nine-bus system. This system naturally includes three machines but in this study a wind farm on the bus 5 is also added. This wind farm includes 30 DFIGs so that total capacity of wind farm is 45 MW. Fig. 9 shows the single line diagram of the case study. The simulation data and parameters for conventional systems are given in [12]. The DFIG parameters are introduced in the Appendix.

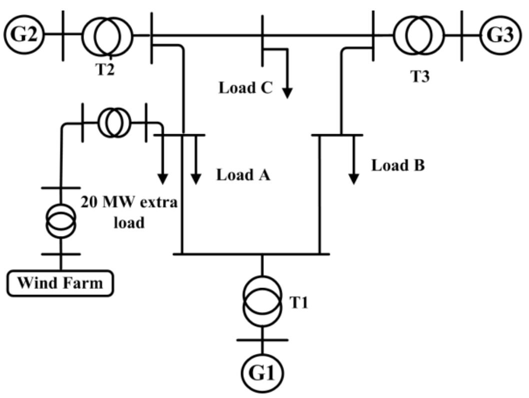

Fig. 9. Case study: updated IEEE nine-bus system with wind farm

In this system, the load increases by 20 MW at t=10s, therefore it causes the imbalance between generation and consumption, and frequency will drop. The synchronous generators for the example at hand are equipped with excitation system and governor, but these units do not have a controller for the LFC purpose. Therefore, the frequency cannot be restored to its nominal value by these units following above disturbance.

V. SIMULATION RESULTS

In this section, the primary control and secondary control are simulated by Matlab/Simulink/SimPowerSystem software. In these simulations, wind speed is considered as 12 meter/sec. Fig. 10 and Fig 11 show the results of primary control. For the K_{pdf} parameter, two values are used: $K_{pdf} = 10$ and $K_{pdf} = 20$. From Fig. 10a, it can be observed that frequency has better condition for $K_{pdf} = 20$, in comparison with the case of $K_{pdf} = 10$, but still the frequency differs from its nominal value. From Fig. 11a, it can be seen that the active power output of wind farm increased at t=10s; but it continuously decreases an overshot; therefore output of synchronous generators will increase (Fig. 10b). From Fig. 11b, it can be observed that the pitch angle starts to decrease at t=10s. Results of secondary control are shown in Fig. 12 and Fig. 13.

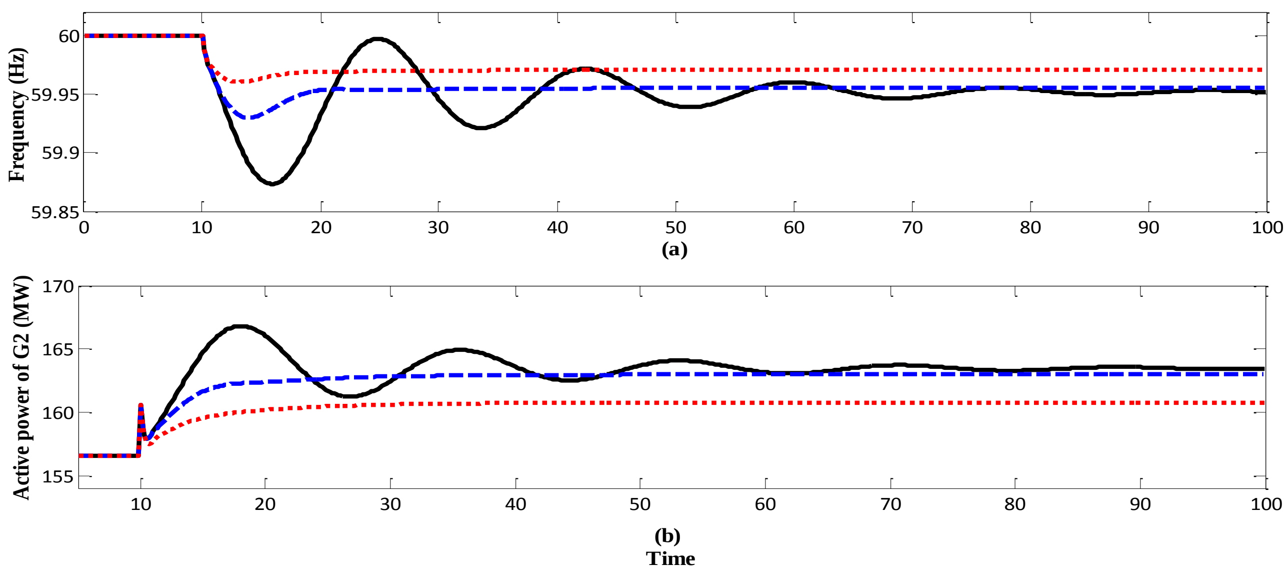

Fig. 10. System responses for primary frequency control; Solid line: without primary control, dashed line: with primary control ($K_{pdf} = 10$), dotted line: with primary control ($K_{pdf} = 20$)

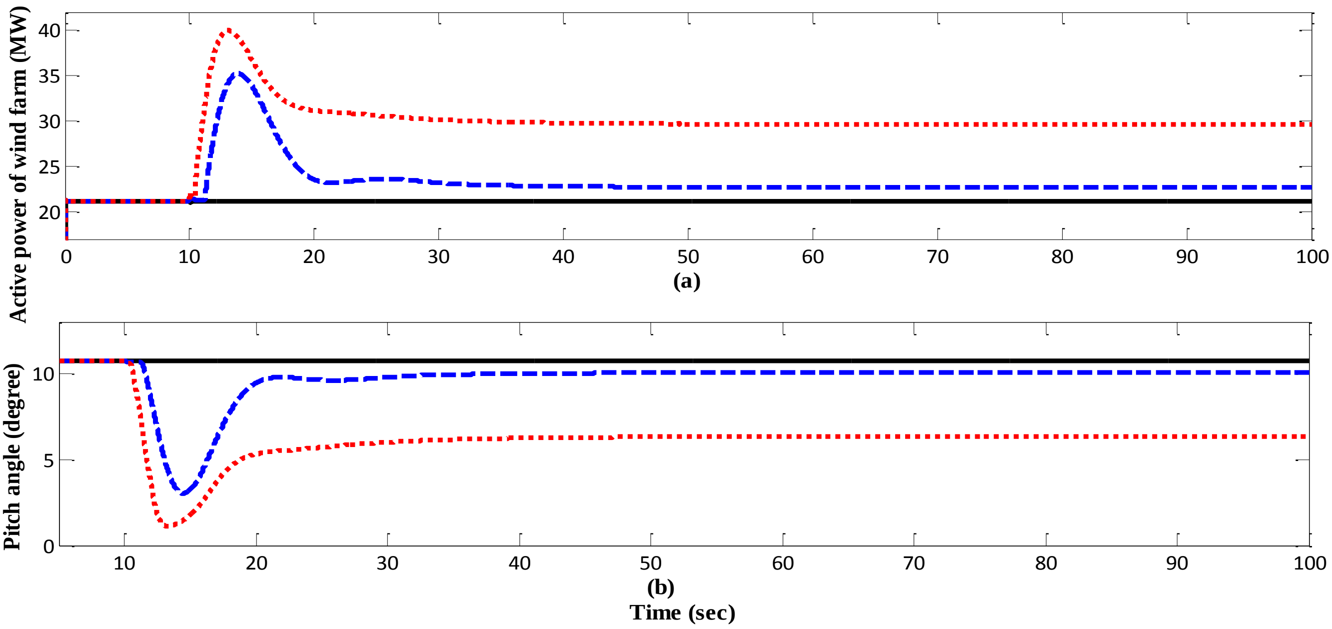

Fig. 11. System responses for primary frequency control; Solid line: without primary control, dashed line: with primary control ($K_{pdf} = 10$), dotted line: with primary control ($K_{pdf} = 20$)

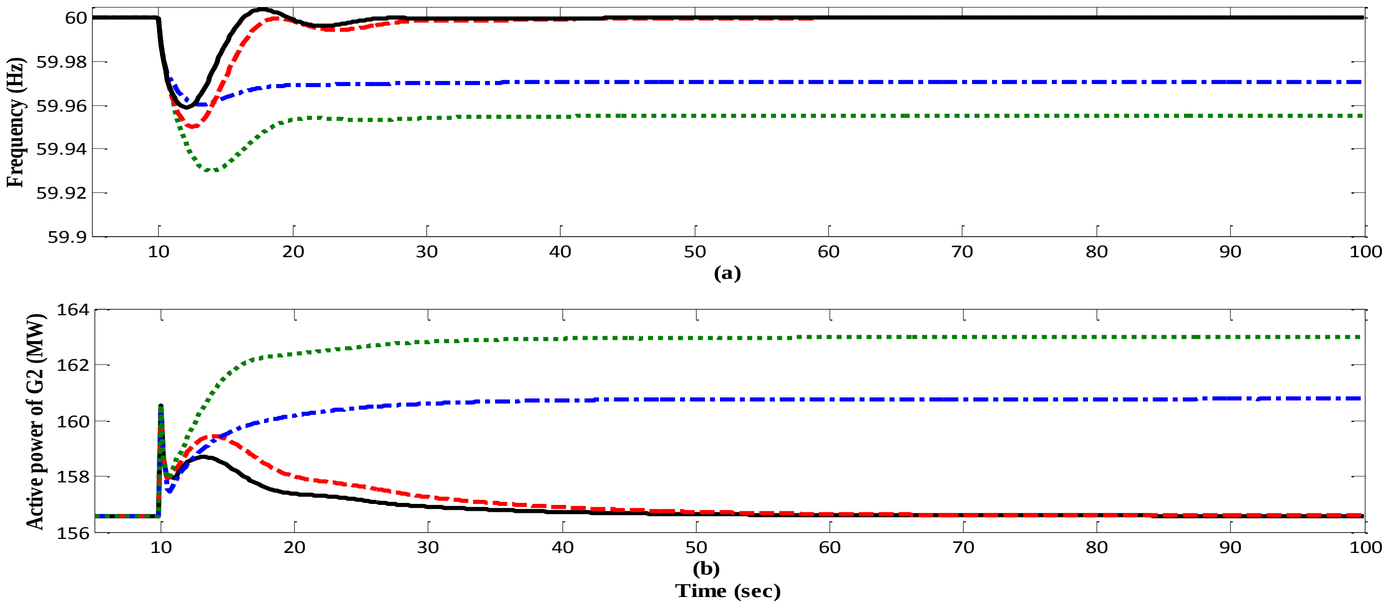

Fig. 12. System responses for primary and secondary frequency control; Solid line: with primary and secondary control ($K_{pdf} = 10, K_p = 1.5, K_i = 5$), dashed line: with primary and secondary control ($K_{pdf} = 10, K_p = 0.3, K_i = 3$), dotted line: with primary control ($K_{pdf} = 10$), dashed dotted line: with primary control ($K_{pdf} = 20$)

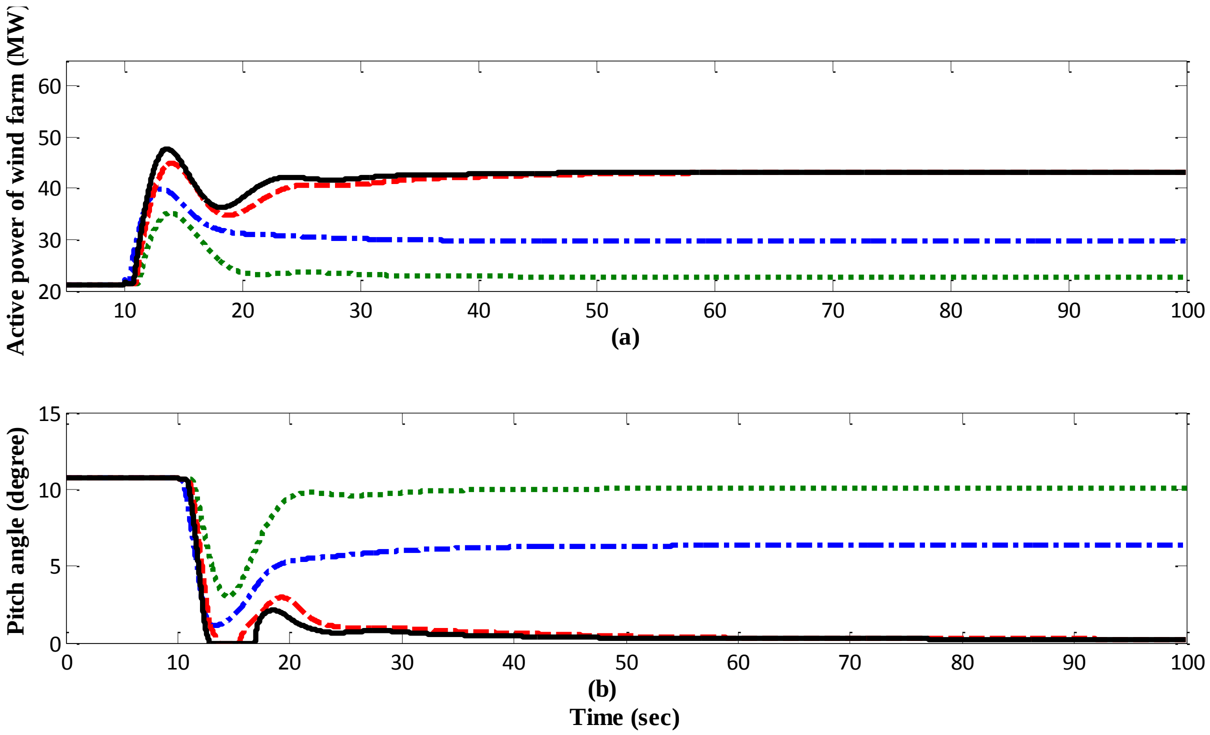

Fig. 13. System responses for primary and secondary frequency control; Solid line: with primary and secondary control ($K_{pdf} = 10, K_p = 1.5, K_i = 5$), dashed line: with primary and secondary control ($K_{pdf} = 10, K_p = 0.3, K_i = 3$), dotted line: with primary control ($K_{pdf} = 10$), dashed dotted line: with primary control ($K_{pdf} = 20$)

From Fig. 12a, it can be seen that using secondary control, the frequency is satisfactorily restored to the nominal value. Active power output of wind farm, which is shown in Fig. 13a, continuously increases until the frequency reaches to its nominal value. In this condition, the outputs of synchronous generators are restored to their nominal values (Fig. 12b); therefore less fuel will be consumed by the conventional units. nominal values (Fig. 12b); therefore less fuel will be consumed by the conventional units.

Fig. 13b shows more reduction in pitch angle in comparison of with Fig. 11b; therefore wind farm uses more wind energy. It is noteworthy that the speed of the DFIG is based on pu of generator synchronous speed.

VI. Conclusion

Nowadays, one of the challenges in the power system operation and control is frequency control in the presence of renewable energy systems. In this paper, firstly, frequency control blocks for the DFIG are explained and previous related works are reviewed and finally, a secondary control loop using well-known PI structure is proposed to restore the system frequency to its nominal value. Simulation results show that following a disturbance, the PI controller satisfactorily compensates the frequency deviations and it is able to restore the frequency to its nominal value.

Appendix

The DFIG parameters: Sn=1.5/0.9 MVA, Vn=575 V, H=5.04s, Rs=0.00706 pu, Ls=0.171 pu, Rr=0.005 pu, Lr=0.156 pu, Lm=2.9 pu.

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