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Performance Evaluation of DFIG to Changes in Network Frequency

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ABSTRACT

Inertia response is the initial response of a generator to the frequency changes of a network and its presence in network is a matter of importance. Synchronous generators have high inertia response naturally. The more tendencies to renewable energies, the more usage of wind power plants in power systems. Due to advantages of doubly fed induction generator (DFIG), this kind of generator constitutes the most wind generators in power plants. Unlike the synchronous generators, DFIGs have negligible inertia response which is caused by generator controller operation. Thus, the evaluation of controller type on its performance is necessary. In this paper, a DFIG with two type of controllers (modified and unmodified) has been simulated in MATLAB/SIMULINK. Besides, the generator operation with network frequency droop conditions has been surveyed and compared as well as the effect of mentioned controllers' action speed on generator's inertia response. The Results showed that the inertia response can be improved significantly by modifying the generator controller system.

Original Article

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INTRODUCTION

Generators and loads connected to power systems in the entire world rely on the strict regulation of system frequency in order to operate perfectly. For obtaining the standard operation in a power system, the frequency must be regulated within corroborated limits by adjusting the electrical supply to meet the demand. If supply and demand would not be balanced, the system frequency will change initially at a rate determined by the total inertia of the system. A generator or load has contribution of inertia of the system if a system frequency changing causes a change in its rotational speed and, thus, its kinetic energy [1]. The inertial response is the power associated with this change in kinetic energy is taken from or fed to the power system. The abrupt loss of supply is the typical initiator of a frequency event. The main factor of determination of the initial falling rate of frequency is the combined inertial response of all remaining electrical machines in the power system. High sensitivity of the frequency that related to the supply-demand imbalance is undesirable obviously. Therefore, it is critical that a large proportion of generation and load contribute to system inertia by providing an inertial response. Note that, the providing of inertial response has more importance for isolated networks or networks with weak interconnection [2, 3].

Analysis of effects of the system frequency changing on speed and kinetic energy of an electrical machine connected to the power system is needed for quantify its inertial response. In conventional synchronous generators, the rotor speed is sensitive to changes in system frequency, and therefore, an inertial response is naturally observable. Thus, if conventional synchronous generators have most contribution of total generation in a power system, the frequency variation will be lower.

In recent years, use of DFIG-based wind turbines has been increased considerably. Thus, a large number of conventional synchronous generators have been displaced by DFIG-based wind turbines.

Mentioned generators have a rotational speed that is decoupled from grid frequency. Reduction in system inertia is expectable, consequently. This is undesirable when there are a large number of DFIG-based wind turbines operating, especially in periods of low load and on smaller power systems. The frequency of a power system with low inertia will change rapidly for abrupt changes in generation or load. In this case, additional frequency response ancillary services must be provided to ensure that frequency limits are not exceeded [4, 5].

Based on above description, many authors have studied issues related to the inertia response of DFIG from different viewpoints. For instance, computer modeling of DFIG for better investigation of its inertia response and analysis of effects of the DFIG controller performance on its inertia response [4], employing a supplementary control loop to the DFIG controller to reintroduce inertia response [6], as well as investigation of effects of the pitch controller on the inertia response [7] are some contributions in this area.

In this paper, a DFIG connected to the infinite bus with simple and modified controller has been simulated in MATLAB®/Simulink® employing a developed model that proposed by Mullaneb et al. [4]. The inertia response of the DFIG with two types of controller (including simple and modified controller) has been analyzed and compared under the dropped frequency conditions. In addition, the effects of controller performance on their inertia response have been investigated. The Results prove that the inertia response can be improved significantly by modifying the generator controller system.

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1. DFIG INERTIA RESPONSE WITH CONVENTIONAL CONTROLLER

A usual DFIG has wounded rotor that its winding ends are connected to the controller through the tumble rings. This controller applies a voltage to rotor with the specific domain and frequency, so that the generator slip is controlled.

With this type of control, when the network frequency drops during the constant wind speed and as a resultant, the speed of rotating stator field is going to decrease, the controller keeps the generator slip and electromagnetic torque stable by changing in the electrical speed of rotating rotor field. Thus, according to equation 3, rotor speed won't change in this conditions and its kinetic energy won't be released. Therefore, while frequency changes; this generator doesn't sense any difference from network so it won't have inertia response. However, due to the fact that the generator's control system has delay like all other control systems, it has negligible inertia response which depends on delay time; because during this delay, the generator will work as a normal electromagnetic generator [4, 5].

In normal electromagnetic generator, by decreasing in system frequency, speed of rotational field of stator will decrease. By decreasing in speed of rotational field of stator, slip that can be result by equation 1 will decrease. Cause of being our investigation in steady state situation, and in this state, slip is too low, relation of electromagnetic torque of this generator will be as equation that is given in the expression 2. It is clear by this equation that by increasing and decreasing in slip, electromagnetic torque will increase and decrease respectively.

In steady state and normal situation, mechanical torque of input and electromagnetic torque of generator are equal and by attention to equation 3, ($d\omega_r/dt$) will be zero. Therefore generator works without changing in rotor speed. But when electromagnetic torque increase which any reason, ($d\omega_r/dt$) will be negative and consequently, rotor speed will decrease. By this decreasing in rotor speed, kinetic energy releases that cause to momentary increase in output power of generator.

$$S = \frac{n_r - n_s}{n_s} \tag{1}$$

$$Te = \frac{3SV_{th}^2}{R_r \omega_S} \tag{2}$$

$$\frac{P_{mech}}{\omega_r} - T_e = j\,\frac{d\omega_r}{dt} \tag{3}$$

$$P_{out} = T_e . \omega_r \tag{4}$$

Where S, n_r, n_s, T_e, V_{th}, R_r, ω_s, ω_r, P_{mech} and P_{out} are slip, rotational field speed of rotor, rotational field speed of stator, electromagnetic torque, the Thevenin equal voltage, rotor resistance, stator electrical angular velocity, rotor electrical angular velocity, mechanical input power and output power of generator respectively.

A complete illustration about the case study and simulations can be found in works of Tayebi-Derazkolaie et al. [5, 8]. In simulation done for the generator, whose considered parameters are shown in table 1, the fault is considered in figure 1 as network frequency drop from 50 Hz to 49.75 Hz exponentially on 70th seconds. It should be noted that before the fault occurred, network frequency was 50Hz and generator delivers power of 2 MW to the infinite bus by having the rotor speed of 100 Rad/S.

By considering 1 second delay time of control system, as it is shown in figure 2, the generator electromagnetic torque increases from 20 KN.m to 20.00025 KN.m at fault time and consequently, the rotor speed decreases from 100 Rad/s to 99.988 Rad/s which is visible in figure 3.

During this slight speed decrease, rotor's kinetic energy decreases from 6950 KJ to 6948.332 KJ and consequently only 1.6KJ energy is released. By releasing this amount of energy, output power increases from 2 MW to 2.0005 MW. As it is seen in figure 4, the change is so low.

Therefore, it is observed that DFIG with conventional controller has negligible inertia response. Hence, because amount of inertia response is negligible, it is suggested to correct its controller by adding a new feedback [6].

TABLE 1. DFIG parameters

Parameter	Value	Unit
P_{out} (rated power)	2×10^6	W
R_S (stator resistance)	1.748×10^{-3}	Ω
R_r (rotor resistance)	3.253×10^{-3}	Ω
L_s (stator inductance)	2.589×10^{-3}	H
L_r (rotor inductance)	2.604×10^{-3}	H
L_m (mutual inductance)	2.492×10^{-3}	H
V_s (generator output voltage)	690	V
j (moment of inertia)	1.39×10^3	Kg/m
T_{in} (input mechanical torque)	2×10^4	N.m
P (number of pole)	6	----
f_s (frequency)	50	Hz

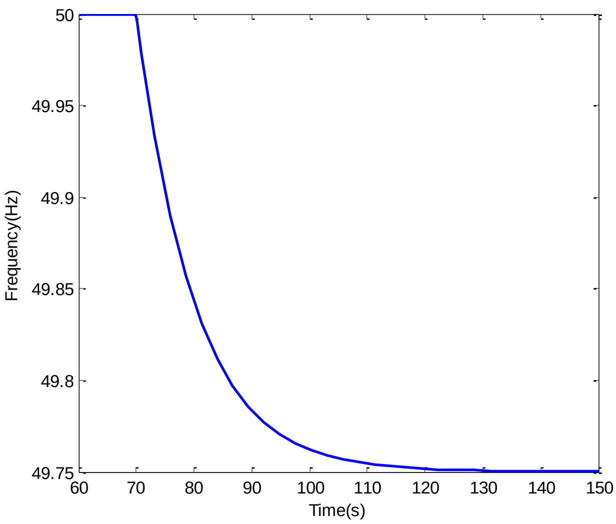

Figure 1: Network Frequency Drop

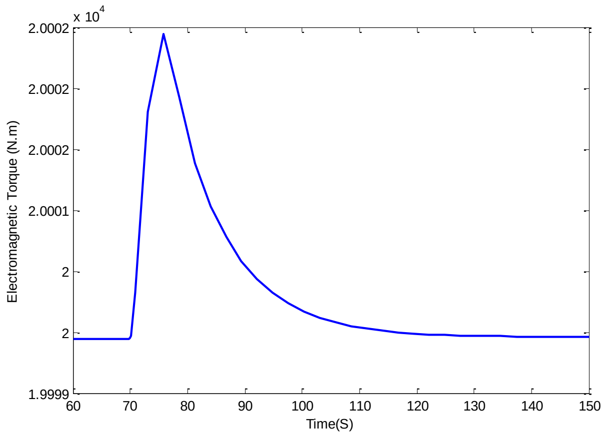

Figure 2: Electromagnetic Torque increasing of DFIG with conventional controller during Fault

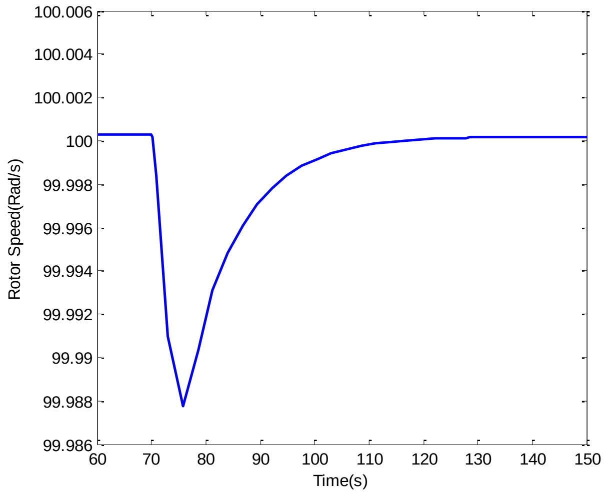

Figure 3: Rotor speed decreasing of DFIG with conventional controller during Fault

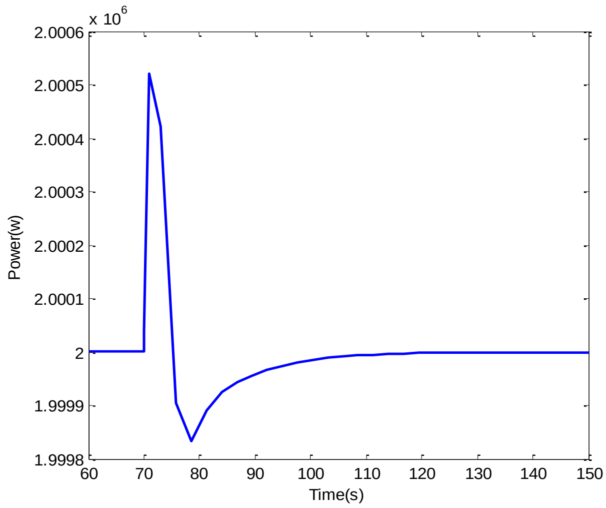

Figure 4: Variation of output power of DFIG with conventional controller during Fault

2. DFIG INERTIA RESPONSE WITH MODIFIED CONTROLLER

As it was observed in previous section the inertia response is near zero in DFIG with conventional controller because the slip is controlled. Conventional controller has a feedback according equation 5. To show inertia response during network frequency changes, according to equation 6 a special feedback is applied to the generator's reference electromagnetic torque in order to change rotor's speed by changing generator electromagnetic torque during network's frequency drop, and consequently generator's kinetic energy is released. So, in this generator, the reference torque in modified state is such as equation 7 [6-10].

$$T_e^* = K_1 \omega_r^2 \tag{5}$$

$$T_e = K_2 \frac{df_S}{dt} \tag{6}$$

$$T_e^* = K_1 \omega_r^2 + K_2 \frac{df_S}{dt} \tag{7}$$

In previous equations, T_e, K_1, K_2, ω_r, P and f_s were respectively reference electromagnetic torque, the main feedback coefficient in control system, increased feedback coefficient, rotor angular speed, mechanical power input and power network frequency.

By adding these feedbacks to reference feedback, when network frequency drops, amount of generator's reference torque increases based on amount of speed and how the network frequency decreases and amount of these feedbacks coefficient. By this increase, according to equation 3, rotor's speed decreases and rotor also releases kinetic energy causing temporarily increase in output power. When system frequency is fixed, derivative amount of frequency is zero, thus the added feedback is removed from circuit and generator is still in its normal operation state. Amount of the feedback's coefficient has direct relationship with amount of rotor's speed drop and inertia response. Therefore according to the limitation of amount of rotor's speed drop and amount of rotor's current increase, amount of this coefficient is limited [7].

In this paper by considering rotor's speed limitation of 85.5 Rad/s (for speed drop), the highest value of this feedback coefficient is considered 500 KN.m using trial and fault. As shown in figures 5 and 6, applying this amount of coefficient and frequency drop, electromagnetic torque increases to 28 KN.m and causes rotor's speed decreases from 100 Rad/s to 85.5 Rad/s. This amount of rotor's speed reduction according to figure 7, causes power increases to 2.66 MW which is better in comparison with the generator inertia response in conventional controller model.

Thus, in DFIG, inertia response can be reached from zero to expressed amount, by adding the feedback to control system and changing the feedback coefficient (depends on conditions).

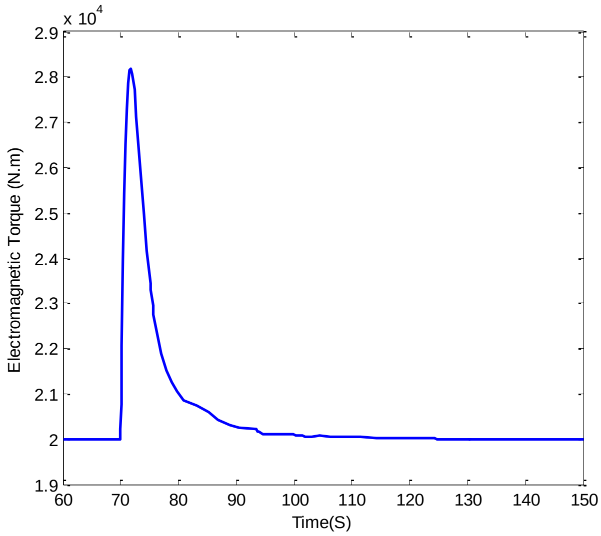

Figure 5: Electromagnetic torque increasing of DFIG with Modified controller during Fault

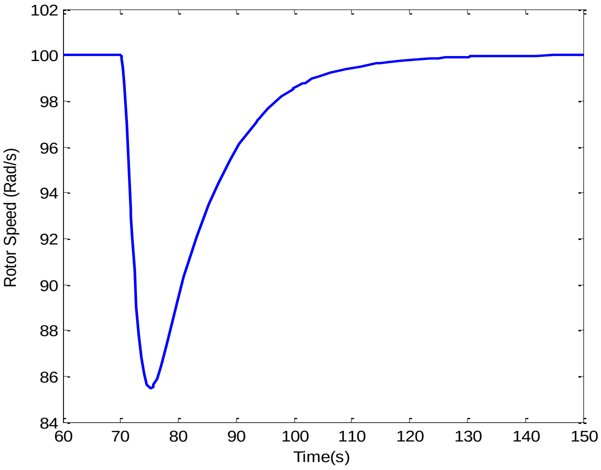

Figure 6: Rotor speed decreasing of DFIG with modified controller during fault

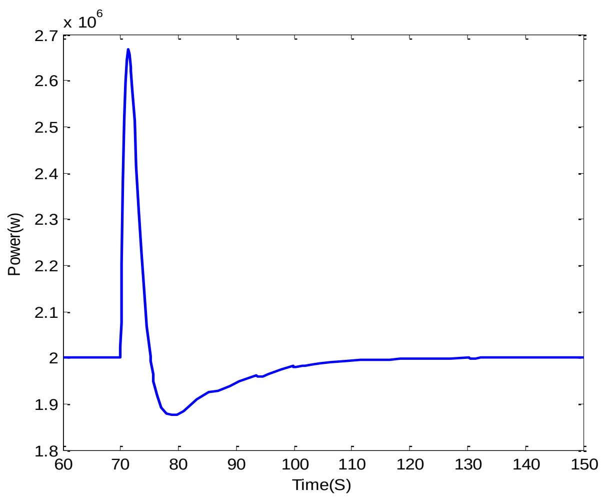

Figure 7: Variation of output power of DFIG with modified controller during fault

3. THE EFFECT OF DFIG WITH CONVENTIONAL CONTROLLER'S PERFORMANCE SPEED ON THE GENERATOR'S INERTIA RESPONSE

It was mentioned in section 2 that amount of delay time in generator control system affect amount of inertia response. In this part, effect of performance speed of DFIG with conventional controller on the generator's inertia response is analyzed. In conventional models, DFIG acts such as a usual electromagnetic generator till the control system has delay. In normal electromagnetic generator, with network frequency drop, speed of stator rotating field decreases. By decreasing in speed of stator rotating field, slip and electromagnetic torque (according to work in steady state) will decrease. At steady state, the input mechanical torque is equal to produced electromagnetic torque and according to equation 3, in this state amount of $d\omega_2/dt$ is zero. Therefore, generator works with a constant rotor speed. When electromagnetic torque increases for some reasons, this quantity will be negative and rotor's speed is reduced and because of this reduction, kinetic energy is released and appears as power in output. Therefore, when DFIG's controller system acts (performs) faster, it prevents the slip change faster and thus inertia response will be reduced [4, 5].

In performed simulation for this generator, to show the effect of controller system performance's speed on the generator's inertia response, the generator's inertia response is surveyed considering different time for controller system's speed. The result will be described and discussed in the following. The generator's electromagnetic torque has been shown in figure 8 with 0.1, 1, 2 second time delay in generator's control system. It is observed in this figure that when 2 seconds time delay were applied, electromagnetic torque increased 2 times more than when time delay was 1 second. But when the time delay was applied 0.1 second, electromagnetic torque almost didn't change. By delay time reduction in control system, electromagnetic torque increase becomes more and according to the mentioned content and equation 3, rotor speed drop will be lower and at this time, rotor releases less kinetic energy. Thus generator's output power increases less which is visible in figure 9. Therefore, it is observed that in DFIG without additional feedback, inertia response decreases by reducing the delay time in controller system performance.

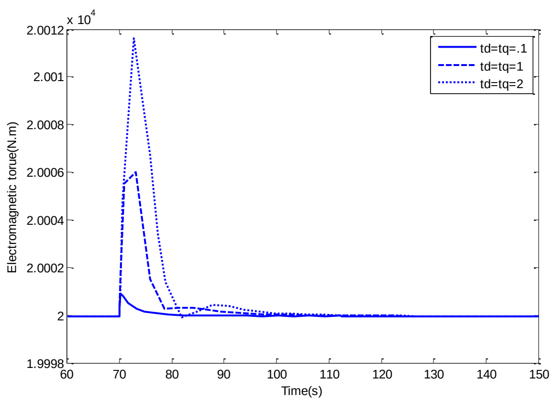

Figure 8: Variation of electromagnetic torque of DFIG with different time constants of controller under network frequency drop

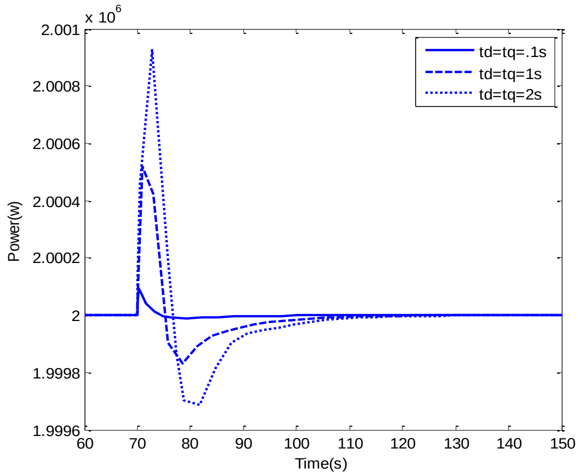

Figure 9: Variation of output power of DFIG with different time constants of controller under network frequency drop

4. The effect of DFIG modified controller's performance speed on the generator's inertia response

In this section, the effect of modified controller performance speed on inertia response quantity is surveyed. When control system performs faster, effect of additional feedback on electromagnetic torque change appears faster. Because usually frequency drop in network is more in the first moment, the most effect on electromagnetic torque change is in first moment. This is clearly visible in figure 10 and as it is obvious in the figure, when delay time is applied for 1 second, electromagnetic torque caused by additional feedback performance increase to 2.8 KN.m (from 2 KN.m). But when the time is increased to 2 second, electromagnetic torque rate decreases to 2.7 KN.m and in case the delay time is applied for 0.1 second, electromagnetic torque increases to 3.2 KN.m.

Therefore, as it was observed, by reducing the control system's delay time, generator electromagnetic torque increases more with additional feedback existence. The more electromagnetic torque increases, the more rotor speed decreases according to equation 3. Consequently, by increasing controller speed, rotor releases more kinetic energy and generator's output power increases temporarily which is visible in figure 11. As it is obvious in this figure when the delay time was applied 0.1 second, generator's output power increased from 2 MW to 3 MW. It increased to 2.66 MW when the delay time was applied 1 second and when the delay time was applied 2 seconds the power increased to 2.55 MW. Thus in DFIG with additional feedback to improve inertia response, the inertia response increases by increasing control system's performance speed.

Another noticeable point in this part was control system performance speed in conventional model of DFIG wasn't important due to low inertia response of generator. But by applying additional feedback causes the generator's inertia response increase, the control system performance speed was very important. Because a small change in time changes the generator inertia response to high level. Thus this delay time reduction is very important.

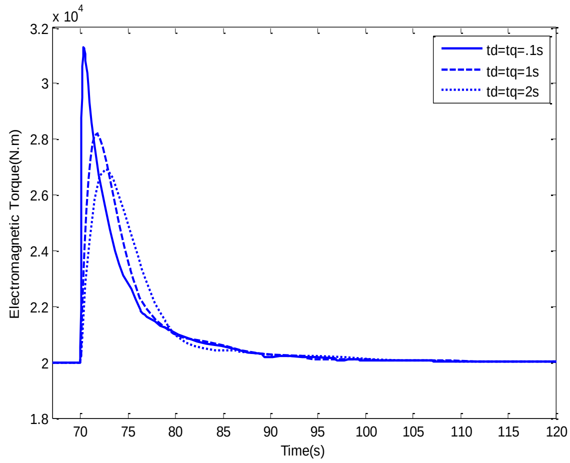

Figure 10: Variation of electromagnetic torque of DFIG with modified controller in different time constants of controller under network frequency drop

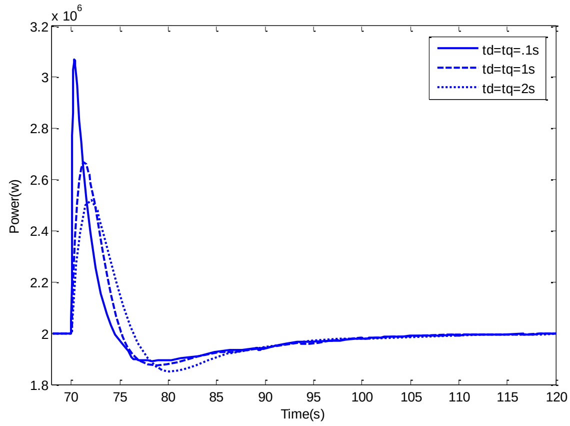

Figure 11: Variation of output power of DFIG with modified controller in different time constants of controller under network frequency drop

Conclusion

Conventional synchronous generators have a good inertia response due to coupling with power system frequency, therefore this type of the network which has many number of such generators is highly resistant to the change in frequency. In recent years, the numbers of wind power plants used in the network increases, and in some cases, were used instead of thermal power plants. Today DFIG becomes the dominant generator in wind power plants due to its high advantages. So analyzing the generator inertia is a matter of importance. It should be mentioned that this generator due to its own special control system, is not affected from network frequency and does not show the proper inertia response so specific feedback can be used to correct this situation. In this paper, by simulating a DFIG in MATLAB environment, inertia response with conventional and modified control models has been analyzed in presence of network frequency drop. So, the following results were obtained:

By adding the feedback, response of inertia increases. The noticeable point in this increase is that the response is controllable by controlling the feedback coefficient so by optimal controlling of this factor, to the extent that the generator is not taken out of its operation, the rotor speed can be changed. Therefore, adding this feedback, the inertia response of the generator can be changed in a wide range.

In DFIG with conventional controller, when the network frequency is changing, while the control system doesn't act, this generator works such as a common induction generator and will have inertia response (of course it is negligible). Therefore, the more speed of control system, the faster compensation of frequency change and the less inertia response, but in modified model, because of the fact that inertia response optimization is caused by control system performance, the more speed of control system leads to increase in inertia response when the network frequency changes. Thus, from the viewpoint of inertia response, in conventional model of DFIG, increase in controller speed is not so important unlike the modified one which the increase in controller speed has a high importance.

DECLARATIONS

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Authors' contribution

All authors contributed equally to this work.

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Competing interest

The authors declare that they have no competing interests.

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