



Dynamic Stability Improvement of Synchronous Generator Using Suggested Controller in Reactive Power Band of DFIG

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ARTICLE INFO	ABSTRACT
<p>Article History: Received 23 December 2021 Received in revised form 12 January 2022 Accepted 8 March 2022 Available online 8 March 2022</p> <p>Keywords: Dynamic Stability, Synchronous Generator, Doubly Fed Induction Generator (DFIG), Reactive Power Band of DFIG, Speed Derivation Feedback, DFIG Electromagnetic Torque Feedback.</p>	<p>Ensuring the stability of synchronous generators is a fundamental challenge in modern power systems, particularly as grid dynamics become increasingly complex. Generator stability is typically classified into three categories: steady-state, dynamic, and transient. This study focuses on dynamic stability, which pertains to the system's ability to maintain synchronism following small disturbances. In parallel, the growing demand for clean energy and the depletion of fossil fuel reserves have accelerated the integration of wind energy into the power grid. Among the various wind generation technologies, the Doubly-Fed Induction Generator (DFIG) has gained prominence due to its operational flexibility and controllability. This paper proposes a control strategy designed to enhance the dynamic stability of synchronous generators using the reactive power control capability of the DFIG. The suggested controller employs two key feedback signals: the rate of change of rotor speed in the synchronous generator and the electromagnetic torque generated by the DFIG. These feedback loops are used to regulate reactive power injection dynamically. The effectiveness of the proposed method is validated through simulations conducted on a test power network subject to two different disturbance scenarios. The results confirm that the controller significantly improves the dynamic response and enhances the overall stability of the synchronous generator.</p>

1. INTRODUCTION

Researchers have been proposed different methods for improving stability of synchronous generator, because it is very important. But we can use DFIG abilities in a network that utilizes wind turbine based on DFIG and increase dynamic stability of synchronous generator. These kinds of wind units are used for generating energy in the network but they can improve dynamic stability of synchronous generator during disturbance occurrence in the system. In fact, we use all of the system capacities by using this job.

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The effect of high power wind turbine based on DFIG on the weak network is evaluated in [1]. So, various tests have been done for different coefficients of load in wind unit and the results prove that DFIG has suitable damping application in these situations.

Investigation in [2], proposes a control scheme based on flywheel saving energy system in order to decrease power fluctuations and improve dynamic stability in wind farm inside sea and connected to the network. A damping controller of PID (Proportional Integral Derivative) by using Modal theory is designed in this reference in order to decrease fluctuations and improve dynamic stability.

A novel method is offered for damping synchronous generator fluctuations and DFIG in multi machine system in order to decrease random effects of wind generations on stability of network in [3]. Particle swarm optimization (PSO) is used for solving this problem.

Reference [4] uses particle swarm optimization (PSO) in controller designing of DFIG for interarea oscillations damping. Wide area measurement system (WAMS) is utilized for being practical of this system. The survey of wind unit effects on power system especially when the capacity of units are impressively high, is done in [5].

Reference [6], explains inertia control scheme based on torque limitation of DFIG that is supporting the frequency control of power system. The proposed scheme decreased the huge volume of twist kinetic energy in DFIG and increase frequency.

A dihedral hierarchy scheme involved local and wide area damping power fluctuations controller that is equipped with DFIG and PSS is offered for damping power fluctuations in [7]. Also, there is facility of stability improvement of two region power system by wind farms inside and within sea by using STATCOM that is assessed in [8].

The purpose of this paper is improving dynamic stability of synchronous generator by using suggested controller for DFIG. This controller uses two feedbacks, synchronous generator speed derivation and DFIG electromagnetic torque. The simulation results show the remarkable improvement of overshoot percentage, settling time and on the other hand phenomenal dynamic stability of synchronous generator in the presence of this controller.

2. MATHEMATICAL MODEL OF SYNCHRONOUS GENERATOR

Reduction order model (order of three) is used for synchronous generator modeling which four order model is obtained by using automatic voltage regulator (AVR) that is observable in Figure 1 [9]. Noted that all of equations are in perunit.

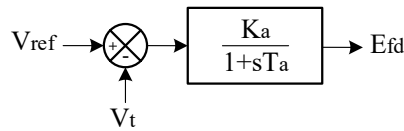


Fig. 1. AVR block diagram

$$\dot{\delta} = \omega_0 \times \Delta\omega \tag{1}$$

$$\Delta\dot{\omega} = \frac{T_m - T_e - D \times \Delta\omega}{2 \times H} \tag{2}$$

$$E'_q = \frac{E_{fd} - E'_q - (x_d - x'_d) \times i_d}{\tau_{do}} \tag{3}$$

$$E_{fd} = \frac{v_{ref} - v_t}{\tau_a} \times K_a - \frac{E_{fd}}{\tau_a} \tag{4}$$

Which in these equations:

$$T_e = v_d \times i_d + v_q \times i_q \tag{5}$$

$$E'_q = \frac{x_{md}}{x_f + x_{md}} \times \psi_f \tag{6}$$

$$E_{fd} = \frac{x_{md}}{R_{fd}} \times v_{fd} \tag{7}$$

$$v_t = \sqrt{v_d^2 + v_q^2} \tag{8}$$

The explanations of variables, parameters and inputs of synchronous generator that are related to equations (1) to (8) are offered in appendix. It is clear the independence variables of synchronous generator are δ , $\Delta\omega$, E'_q and E'_{fd} respectively and its inputs are v_{ref} and T_m by noting to equations (1) to (4).

3. MATHEMATICAL MODEL OF DFIG

Five order model of induction generator is used for DFIG modeling. Differential equations are [10]:

$$\dot{\psi}_{qs} = \omega_0 \times (v_{qs} - \omega \times \psi_{ds} - R_s \times i_{qs}) \tag{9}$$

$$\dot{\psi}_{ds} = \omega_0 \times (v_{ds} + \omega \times \psi_{qs} - R_s \times i_{ds}) \tag{10}$$

$$\dot{\psi}'_{qr} = \omega_0 \times (v'_{qr} - (\omega - \omega_r) \times \psi'_{dr} - R'_r \times i'_{qr}) \tag{11}$$

$$\dot{\psi}'_{dr} = \omega_0 \times (v'_{dr} + (\omega - \omega_r) \times \psi'_{qr} - R'_r \times i'_{dr}) \tag{12}$$

$$\dot{\omega}_r = \frac{T_e - T_m}{2 \times H} \tag{13}$$

Which in the above equations:

$$i_{qs} = \frac{x_{lr} + x_m}{x_{lr}x_m + x_{lr}x_{ls} + x_{ls}x_m} \psi_{qs} - \frac{x_m}{x_{lr}x_m + x_{lr}x_{ls} + x_{ls}x_m} \psi'_{qr} \tag{14}$$

$$i_{ds} = \frac{x_{lr} + x_m}{x_{lr}x_m + x_{lr}x_{ls} + x_{ls}x_m} \psi_{ds} - \frac{x_m}{x_{lr}x_m + x_{lr}x_{ls} + x_{ls}x_m} \psi'_{dr} \tag{15}$$

$$i'_{qr} = \frac{x_{ls} + x_m}{x_{lr}x_m + x_{lr}x_{ls} + x_{ls}x_m} \psi'_{qr} - \frac{x_m}{x_{lr}x_m + x_{lr}x_{ls} + x_{ls}x_m} \psi_{qs} \tag{16}$$

$$i'_{dr} = \frac{x_{ls} + x_m}{x_{lr}x_m + x_{lr}x_{ls} + x_{ls}x_m} \psi'_{dr} - \frac{x_m}{x_{lr}x_m + x_{lr}x_{ls} + x_{ls}x_m} \psi_{ds} \tag{17}$$

$$T_e = \psi_{ds} \times i_{qs} - \psi_{qs} \times i_{ds} \tag{18}$$

It is noted that equations (9) to (18) are completely in perunit and the explanations of variables, parameters and inputs are offered in appendix.

4. DFIG CONTROLLERS

By noting to equations that are described in the previous part, for DFIG we have two variables v'_{dr} and v'_{qr} which are able to control two variables when get commands from control circuits. These variables are DFIG electromagnetic torque and stator reactive power respectively. Used controllers in this paper are PI type. These control circuits are shown in Figure 2.

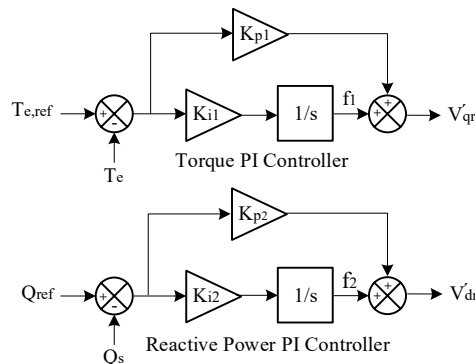


Fig. 2. Control circuits of DFIG

Two differential equations could be extracted from these controllers. These equations are:

$$\dot{f}_1 = K_{i1} \times (T_{e,ref} - T_e) \tag{19}$$

$$\dot{f}_2 = K_{i2} \times (Q_{ref} - Q_s) \tag{20}$$

And finally the rotor voltage value is obtained in d and q axis as below:

$$\dot{u}_1 = \frac{K \times K_2 \times (T_{e,ref} - T_e)}{\tau} + \frac{K \times K_1 \times \Delta\omega}{\tau} - \frac{u_1}{\tau} \quad (23)$$

Also by noting to this controller, equations (20) and (22) are modified as bellow:

$$\dot{f}_2 = K_{i2} \times (u_1 + Q_{ref} - Q_s) \quad (24)$$

$$v'_{dr} = f_2 + K_{p2} \times (u_1 + Q_{ref} - Q_s) \quad (25)$$

In the above equations, K , K_1 , K_2 and τ are main gain of controller, feedback gain of speed derivation in synchronous generator, feedback gain of DFIG electromagnetic torque and time constant of controller respectively. As mentioned above by noting to equation (23) by using suggested controller, a state variable is added to the summation of independent state variables of system.

6. TEST NETWORK

Test network that is used in this paper, is offered in Figure 5. This figure includes synchronous generator, wind turbine based on DFIG, transmission line and infinite bus. Network equations are explained analytical according to equations (40) to (45) because all of the synchronous generator, DFIG and controllers equations, are analytical.

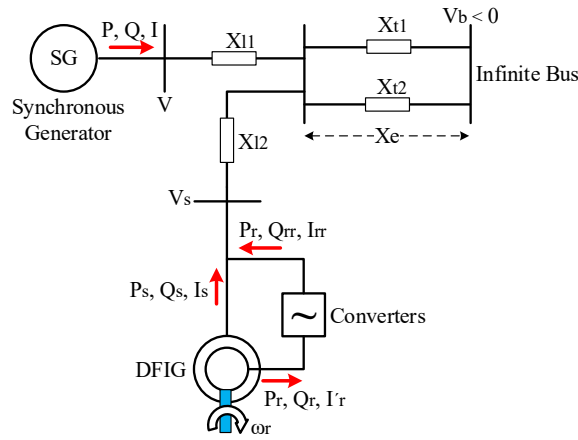


Fig. 5. Test network

Which in the Figure 5:

$$X_e = X_{t1} \parallel X_{t2} \quad (26)$$

$$V = v_q - j \times v_d, V_s = v_{qs} - j \times v_{ds} \quad (27)$$

$$I = i_q - j \times i_d, I_s = i_{qs} - j \times i_{ds}, I'_r = i'_{qr} - j \times i'_{dr}, I_{rr} = i_{qrr} - j \times i_{drr} \quad (28)$$

The relations between voltage and current in synchronous generator are:

$$i_d = \frac{E'_q - v_q}{x'_d} \quad (29)$$

$$i_q = \frac{v_d}{x_q} \quad (30)$$

Also the relations of stator and rotor active and reactive power of DFIG are:

$$P_s = v_{ds} \times i_{ds} + v_{qs} \times i_{qs} \quad (31)$$

$$Q_s = v_{qs} \times i_{ds} - v_{ds} \times i_{qs} \quad (32)$$

$$P_r = v'_{dr} \times i'_{dr} + v'_{qr} \times i'_{qr} \quad (33)$$

$$Q_r = v'_{qr} \times i'_{dr} - v'_{dr} \times i'_{qr} \quad (34)$$

By ignoring the loss of active power and supposing zero output reactive power of converters:

$$I_{rr} = i_{qrr} - j \times i_{drr} = \left(\frac{P_r + j \times Q_{rr}}{v_{qs} - j \times v_{ds}} \right)^* \xrightarrow{Q_{rr}=0} I_{rr} = \left(\frac{P_r}{v_{qs} + j \times v_{ds}} \right) = \frac{P_r \times v_{qs}}{v_{qs}^2 + v_{ds}^2} - j \frac{P_r \times v_{ds}}{v_{qs}^2 + v_{ds}^2} \quad (35)$$

Network equations are:

$$V = jX_{l1} \times I - jX_e \times (I - I_s - I_{rr}) + (V_b \times \cos(\delta) - j V_b \times \sin(\delta)) \quad (36)$$

$$V_s = jX_{l1} \times I + jX_{l2} \times (I_s + I_{rr}) \quad (37)$$

By opening the equations (36) and (37):

$$v_q = V_b \times \cos(\delta) + (X_{l1} + X_e)i_d - X_e \times (i_{ds} + i_{drr}) \quad (38)$$

$$v_d = V_b \times \sin(\delta) - (X_{l1} + X_e)i_q + X_e \times (i_{qs} + i_{qrr}) \quad (39)$$

$$v_{qs} = v_q - X_{l1} \times i_d - X_{l2} \times (i_{ds} + i_{drr}) \quad (40)$$

$$v_{ds} = v_d + X_{l1} \times i_q + X_{l2} \times (i_{qs} + i_{qrr}) \quad (41)$$

7. SIMULATION

Test network of Figure 5 (which its elements characteristics are completely in the appendix) is used for simulation. Simulation is done in two steps for two dynamic disturbances that are mechanical torque increasing of synchronous generator and increasing reference voltage of AVR.

7.1. First step: Mechanical torque increasing of synchronous generator

In this step, we suppose that mechanical torque of synchronous generator is increased from 0.7 perunit with 0.1 to 0.8 perunit in second 40 of simulation. The information of this step is in Table 1.

Table 1. The first step information

Synchronous generator reference voltage (v_{ref})	1.06 pu
DFIG mechanical torque (T_m)	-0.3 pu
DFIG reference torque ($T_{e,ref}$)	-0.3 pu
DFIG reference reactive power (Q_{ref})	0 pu

Figure 6 displays some variables of synchronous generator and DFIG and then two states mean utilizing suggested controller and non-utilizing that are compared to each other.

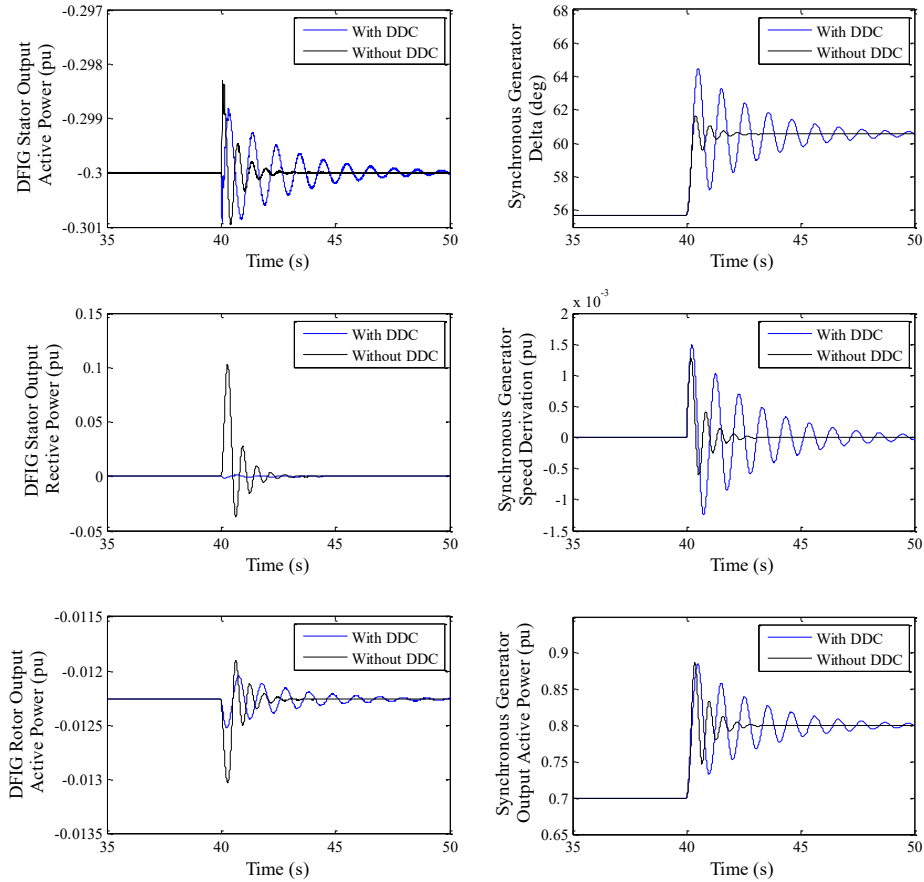


Fig. 6. Suggested controller effects on dynamic stability of synchronous generator (First step)

By observing the Figure 6, domain of fluctuations and settling time are decreased impressively in the presence of suggested controller. This subject is visible in the synchronous generator variables and more important power angle of that. The settling time is decreased from 18 seconds to 4 seconds and overshoot percentage is decreased from 80% to 20%.

7.2. Second step: Reference voltage increasing of AVR

In the second step, reference voltage is increased 0.01 perunit in second 35 of simulation. The information of this step is offered in Table 2.

Table 2. Second step information

Output power of synchronous generator	0.7 pu
DFIG mechanical torque (T_m)	-0.3 pu
DFIG reference torque ($T_{e,ref}$)	-0.3 pu
DFIG reference reactive power (Q_{ref})	0 pu

The trend of this step is similar to previous step. In Figure 7, some synchronous generator and DFIG variables are displayed in two states.

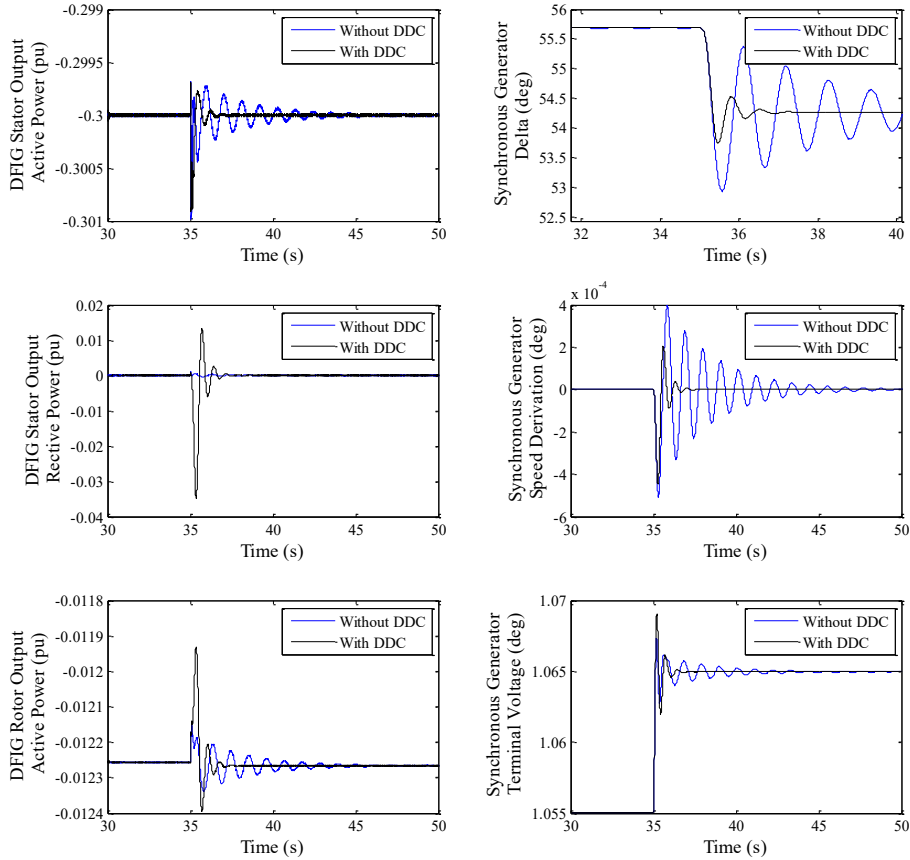


Fig. 7. Suggested controller effects on dynamic stability of synchronous generator (Second step)

In this step, according to last step, the effects of suggested controller on dynamic stability of synchronous generator and its variables such as power angle is completely apparent. For example in the plot of power angle of synchronous generator, the settling time is decreased from 15 seconds to 3 seconds and overshoot percentage is decreased from 90% to 30%.

8. CONCLUSION

Stability improvement of synchronous generator is the most basic concern of researchers. If the network concludes wind turbines based on DFIG, we can do it by using suggested controller in DFIG. Proposed controller and the structure of that have been offered in this paper and its operating has been studied during two disturbances in the test network. The obtained results of overshoot and settling time were surprising because the improvement in the mentioned indexes was about 3 to 5 times. These results show that the controller does its job means synchronous generator dynamic stability improvement correctly.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

9. APPENDIX

The explanation of synchronous generator and DFIG variables, parameters and inputs are:

Synchronous generator:

δ	Power angle
$\Delta\omega$	Speed derivation
E'_q	Inducted voltage resulted of ψ_f
E_{fd}	Voltage resulted of v_{fd}
T_e	Electromagnetic torque
v_t	Terminal voltage
v_d	d axis terminal voltage
i_d	d axis output current
v_q	q axis terminal voltage
i_q	q axis output current
ψ_f	Exciter circuit flux
v_{fd}	Exciter winding voltage
ω_0	Synchronous speed
D	Damping coefficient
H	Inertia
x_d	d axis reactance
x'_d	d axis transient reactance
τ'_{do}	d axis transient time constant
x_{md}	d axis magnetic reactance
x_f	Exciter winding reactance
R_{fd}	Exciter winding resistance
T_m	Motive mechanical torque
v_{ref}	Reference terminal voltage
K_a	AVR gain
τ_a	AVR time constant

DFIG:

ψ_{qs}	q axis stator flux
ψ_{ds}	d axis stator flux
ψ'_{qr}	q axis rotor flux
ψ'_{dr}	d axis rotor flux
ω_r	DFIG rotor speed
i_{qs}	q axis stator current
i_{ds}	d axis stator current
i'_{qr}	q axis rotor current
i'_{dr}	d axis rotor current
T_e	Electromagnetic torque
v_{qs}	q axis stator voltage
v_{ds}	d axis stator voltage
v'_{qr}	q axis rotor voltage
v'_{dr}	d axis rotor voltage
ω_0	Synchronous speed
H	Inertia
ω	Reference frame speed
R_s	Stator winding resistance
R'_r	Rotor winding resistance
x_{ls}	Stator winding reactance
x_{lr}	Rotor winding reactance
x_m	Magnetic reactance
T_m	Motive mechanical torque

The values of synchronous generator, DFIG, its controllers, suggested controller and network are according below. It is really important that all of the values are in perunit system.

Synchronous generator:

ω_0	100 π
D	0
H	5
x_d	1.8
x'_d	0.1
τ'_{do}	10
K_a	400

DFIG:

τ_a	0.1
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ω_0	100π
H	4
ω	100π
R_s	0.01
R_r'	0.02
x_{ls}	0.01
x_{lr}	0.01
x_m	5

DFIG controllers:

K_{p1}	0.1
K_{i1}	10
K_{p2}	0.1
K_{i2}	10

Suggested controller:

K	2
K_1	50
K_2	1
τ	0.1

Test network:

X_{l1}	0.05
X_{l2}	0.025
X_{t1}	0.6
X_{t2}	0.6
V_b	1

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