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

A. Alavi Eshkaftaki¹, A. Rabiee², A. Kargar³*, S. Taghipour Boroujeni⁴

¹,²,³,⁴ Department of electrical engineering, Shahrekord University, Shahrekord, Iran

ABSTRACT

Stability of synchronous generator and its improvement is one of the important problems in the power system. Stability can be divided into three kinds: steady state, dynamic and transient which we study here about dynamic stability in this paper. Nowadays pollution crisis in one hand and running out resources of fossil fuels on the other hand are caused increasing wind generations using based on doubly fed induction generator (DFIG). One of the abilities of DFIG is using it in order to improve dynamic stability in synchronous generator. In this paper, a suggested controller is used in the reactive power band of DFIG in order to increase dynamic stability of synchronous generator. This controller uses two feedbacks of speed derivation in synchronous generator and DFIG electromagnetic torque feedback. Finally, the simulation results for two disturbances in the test network show the suggested controller works correctly and the dynamic stability of synchronous generator has been increased remarkably.

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.

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.

* Corresponding Author: kargar@ieee.org
Department of Electrical Engineering, Shahrekord University, Shahrekord, Iran

http://dx.doi.org/10.47176/TMI.2022.11
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.

\[ V_{ref} \rightarrow \begin{array}{ccc} \times & K_a & \text{Efd} \\ \downarrow & \downarrow & \downarrow \\ V_t & \frac{1}{1+sT_a} & \end{array} \]

\[ \delta = \omega_0 \times \Delta \omega \]  
\[ \Delta \omega = \frac{T_m - T_e - \Delta \omega}{2\kappa H} \]  
\[ E_q' = \frac{E_{fd} - E_q'}{\tau_q} \times (x_d - x_q) \times \frac{1}{\tau_d} \]  
\[ E_{fd} = \frac{v_{ref} - v_{t}}{\tau_a} \times K_a - \frac{E_{fd}}{\tau_a} \]  

Which in these equations:
\[ T_e = v_d \times l_d + v_q \times l_q \]  
\[ E_q' = \frac{x_{md}}{x_f + x_{md}} \times \psi_f \]  
\[ E_{fd} = \frac{x_{md}}{R_{fd}} \times v_{fd} \]  
\[ v_t = \sqrt{v_d^2 + v_q^2} \]

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 \( \delta, \Delta \omega, E_q' \) 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]:

\[
\begin{align*}
\dot{\psi}_{qs} &= \omega o \times (v_{qs} - \omega \times \psi_{ds} - R_s \times i_{qs}) \\
\dot{\psi}_{ds} &= \omega o \times (v_{ds} + \omega \times \psi_{qs} - R_s \times i_{ds}) \\
\dot{\psi}_{qr} &= \omega o \times (v'_{qr} - (\omega - \omega_r) \times \psi_{dr}^r - R'_s \times i'_{qr}) \\
\dot{\psi}_{dr} &= \omega o \times (v'_{dr}^r + (\omega - \omega_r) \times \psi_{qr}^r - R'_s \times i'_{dr}) \\
\dot{\omega}_r &= \frac{T_e - T_m}{2 \times H}
\end{align*}
\]

Which in the above equations:

\[
\begin{align*}
i_{qs} &= \frac{x_{lr} + x_m}{x_{lr} + x_m} \psi_{qs} - \frac{x_m}{x_{lr} + x_m + x_{ls} + x_{ls}^m} \psi_{qr} \\
i_{ds} &= \frac{x_{lr} + x_m}{x_{lr} + x_m} \psi_{ds} - \frac{x_m}{x_{lr} + x_m + x_{ls} + x_{ls}^m} \psi_{dr} \\
i_{qr} &= \frac{x_{lr} + x_m}{x_{lr} + x_m + x_{ls} + x_{ls}^m} \psi_{qr} - \frac{x_m}{x_{lr} + x_m + x_{ls} + x_{ls}^m} \psi_{qs} \\
i_{dr} &= \frac{x_{lr} + x_m}{x_{lr} + x_m + x_{ls} + x_{ls}^m} \psi_{dr} - \frac{x_m}{x_{lr} + x_m + x_{ls} + x_{ls}^m} \psi_{ds} \\
T_e &= \psi_{ds} \times i_{qs} - \psi_{qs} \times i_{ds}
\end{align*}
\]

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:

\[
\begin{align*}
\dot{f}_1 &= K_{i1} \times (T_{e,ref} - T_e) \\
\dot{f}_2 &= K_{i2} \times (Q_{ref} - Q_s)
\end{align*}
\]

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

\[
\begin{align*}
v'_{qr} &= f_1 + K_{p1} \times (T_{e,ref} - T_e) \\
v'_{dr} &= f_2 + K_{p2} \times (Q_{ref} - Q_s)
\end{align*}
\]
In equations (19) to (22) the parameters $K_{p1}$, $K_{p2}$, $K_{i1}$ and $K_{i2}$ are proportional and integral coefficients in DFIG controllers respectively. Based on these equations, there are seven state variables for DFIG and they are $\psi_{qs}$, $\psi_{ds}$, $\psi'_{qr}$, $\psi'_{dr}$, $\omega_r$, $f_1$ and $f_2$ respectively. And the inputs of DFIG are $T_m$, $T_{e,ref}$ and $Q_{ref}$.

These controllers are observable in Figure 3. In this figure, $\delta$ (power angle of synchronous generator) is used for changing abc to qd reference in stator side and the difference of that to DFIG rotor angle from integrator block is used in rotor side. In fact the speed of synchronous generator is used as a reference frame.

Fig. 3. DFIG controllers

5. SUGGESTED CONTROLLER

The aim of suggested controller is improving dynamic stability of synchronous generator. The facility of using this controller is provided in both DFIG electromagnetic torque and reactive power band. But reactive power band is used in this paper. The situation of this controller is shown in Figure 3 and the structure of that is according to Figure 4. Two feedbacks, speed derivation of synchronous generator and DFIG electromagnetic torque are used in this controller by noting these figures. The output of this controller is a signal that it will damp dynamic fluctuations strongly. This topic is proved in simulations and results of that. By noting to Figure 4 and attention to this controller a state variable has been added to the summation of system state variables and the name of this variable is $u_1$.

Fig. 4. Suggested controller in the DFIG reactive power band with synchronous generator speed derivation and DFIG electromagnetic torque feedbacks

Differential equation related to suggested controller is:

$$u_1 = \frac{K \times K_2 \times (T_{e,ref} - T_e)}{\tau} + \frac{K \times K_1 \times \Delta \omega}{\tau} - \frac{u_1}{\tau}$$  \hspace{1cm} (23)

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

$$f_2 = K_{i2} \times (u_1 + Q_{ref} - Q_s)$$  \hspace{1cm} (24)
\[ v'_{dr} = f_2 + K_{p2} \times (u_1 + Q_{ref} - Q_s) \] (25)

In the above equations, \( K, K_1, K_2 \) and \( \tau \) 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.

![Test network diagram](https://via.placeholder.com/150)

**Fig. 5. Test network**

Which in the Figure 5:
\[ X_e = X_{l1} \parallel X_{l2} \]
\[ V = v_q - j \times v_d, \ V_s = v_{qs} - j \times v_{ds} \]
\[ I = i_q - j \times i_d, \ I_s = i_{qs} - j \times i_{ds}, \ I'_r = i'_{qr} - j \times i'_{dr}, \ I_{rr} = i_{qrr} - j \times i_{drr} \]

The relations between voltage and current in synchronous generator are:
\[ \begin{align*}
  i_d &= \frac{v_d - v_q}{x'_d} \\
  i_q &= \frac{v_q}{x_q}
\end{align*} \] (29) (30)

Also the relations of stator and rotor active and reactive power of DFIG are:
\[ \begin{align*}
  P_s &= v_d \times i_d + v_{qs} \times i_{qs} \\
  Q_s &= v_q \times i_d - v_{ds} \times i_{qs} \\
  P_r &= v'_d \times i'_d + v'_{qr} \times i'_{qr} \\
  Q_r &= v'_q \times i'_d - v'_{dr} \times i'_{qr}
\end{align*} \] (31) (32) (33) (34)

By ignoring the loss of active power and supposing zero output reactive power of converters:
\[ I_{rr} = i_{qrr} - j \times i_{drr} = \frac{P_r + j \times Q_r}{v_{qs} - j \times v_{ds}} \]
\[ I_{rr} = \frac{P_r}{v_{qs} + j \times v_{ds}} = \frac{P_r \times v_{qs}}{v_{qs}^2 + v_{ds}^2} - j \frac{P_r \times v_{ds}}{v_{qs}^2 + v_{ds}^2} \] (35)

Network equations are:
\[ \begin{align*}
  V &= jX_{l1} \times I - jX_e \times (I - I_s - I_{rr}) + (V_b \times \cos(\delta) - j V_b \times \sin(\delta)) \\
  V_s &= jX_{l1} \times I + jX_{l2} \times (I_s + I_{rr})
\end{align*} \] (36) (37)

By opening the equations (36) and (37):
\[ \begin{align*}
  v_q &= V_b \times \cos(\delta) + (X_{l1} + X_e) i_d - X_e \times (i_{ds} + i_{drr}) \\
  v_d &= V_b \times \sin(\delta) - (X_{l1} + X_e) i_q + X_e \times (i_{qs} + i_{qrr}) \\
  v_{qs} &= v_q - X_{l1} \times i_d - X_{l2} \times (i_{ds} + i_{drr})
\end{align*} \] (38) (39) (40)
\[ v_{ds} = v_d + X_{l1} \times i_q + X_{l2} \times (i_{qs} + i_{qr}) \]  

(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>
<thead>
<tr>
<th>Table 2. Second step information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power of synchronous generator</td>
</tr>
<tr>
<td>DFIG mechanical torque ($T_m$)</td>
</tr>
<tr>
<td>DFIG reference torque ($T_{e,ref}$)</td>
</tr>
<tr>
<td>DFIG reference reactive power ($Q_{ref}$)</td>
</tr>
</tbody>
</table>

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.

9. APPENDIX

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

Synchronous generator:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta )</td>
<td>Power angle</td>
</tr>
<tr>
<td>( \Delta \omega )</td>
<td>Speed derivation</td>
</tr>
<tr>
<td>( E'_q )</td>
<td>Inducted voltage resulted of ( \psi_f )</td>
</tr>
<tr>
<td>( E_{fd} )</td>
<td>Voltage resulted of ( v_{ld} )</td>
</tr>
<tr>
<td>( T_e )</td>
<td>Electromagnetic torque</td>
</tr>
<tr>
<td>( v_t )</td>
<td>Terminal voltage</td>
</tr>
<tr>
<td>( v'_{d} )</td>
<td>d axis terminal voltage</td>
</tr>
<tr>
<td>( i_d )</td>
<td>d axis output current</td>
</tr>
<tr>
<td>( v'_{q} )</td>
<td>q axis terminal voltage</td>
</tr>
<tr>
<td>( i_q )</td>
<td>q axis output current</td>
</tr>
<tr>
<td>( \psi_f )</td>
<td>Exciter circuit flux</td>
</tr>
<tr>
<td>( v_{fd} )</td>
<td>Exciter winding voltage</td>
</tr>
<tr>
<td>( \omega \sigma )</td>
<td>Synchronous speed</td>
</tr>
<tr>
<td>( D )</td>
<td>Damping coefficient</td>
</tr>
<tr>
<td>( H )</td>
<td>Inertia</td>
</tr>
<tr>
<td>( x_d )</td>
<td>d axis reactance</td>
</tr>
<tr>
<td>( x'_d )</td>
<td>d axis transient reactance</td>
</tr>
<tr>
<td>( \tau_{do} )</td>
<td>d axis transient time constant</td>
</tr>
<tr>
<td>( x_{md} )</td>
<td>d axis magnetic reactance</td>
</tr>
<tr>
<td>( x_f )</td>
<td>Exciter winding reactance</td>
</tr>
<tr>
<td>( R_{fa} )</td>
<td>Exciter winding resistance</td>
</tr>
<tr>
<td>( T_m )</td>
<td>Motive mechanical torque</td>
</tr>
<tr>
<td>( v_{ref} )</td>
<td>Reference terminal voltage</td>
</tr>
<tr>
<td>( K_a )</td>
<td>AVR gain</td>
</tr>
<tr>
<td>( \tau_a )</td>
<td>AVR time constant</td>
</tr>
</tbody>
</table>

DFIG:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \psi_{qs} )</td>
<td>q axis stator flux</td>
</tr>
<tr>
<td>( \psi_{ds} )</td>
<td>d axis stator flux</td>
</tr>
<tr>
<td>( \psi'_{qr} )</td>
<td>q axis rotor flux</td>
</tr>
<tr>
<td>( \psi'_{dr} )</td>
<td>d axis rotor flux</td>
</tr>
<tr>
<td>( \omega_r )</td>
<td>DFIG rotor speed</td>
</tr>
<tr>
<td>( i_{qr} )</td>
<td>q axis stator current</td>
</tr>
<tr>
<td>( i_{qs} )</td>
<td>d axis stator current</td>
</tr>
<tr>
<td>( i'_{qr} )</td>
<td>q axis rotor current</td>
</tr>
<tr>
<td>( i'_{qs} )</td>
<td>d axis rotor current</td>
</tr>
<tr>
<td>( T_e )</td>
<td>Electromagnetic torque</td>
</tr>
<tr>
<td>( v_{qs} )</td>
<td>q axis stator voltage</td>
</tr>
<tr>
<td>( v_{ds} )</td>
<td>d axis stator voltage</td>
</tr>
<tr>
<td>( v'_{qr} )</td>
<td>q axis rotor voltage</td>
</tr>
<tr>
<td>( v'_{dr} )</td>
<td>d axis rotor voltage</td>
</tr>
<tr>
<td>( \omega_0 )</td>
<td>Synchronous speed</td>
</tr>
<tr>
<td>( H )</td>
<td>Inertia</td>
</tr>
<tr>
<td>( \omega )</td>
<td>Reference frame speed</td>
</tr>
<tr>
<td>( R_s )</td>
<td>Stator winding resistance</td>
</tr>
<tr>
<td>( R'_r )</td>
<td>Rotor winding resistance</td>
</tr>
<tr>
<td>( x_{ls} )</td>
<td>Stator winding reactance</td>
</tr>
</tbody>
</table>
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:

\[
\begin{align*}
\omega_0 & = 100 \pi \\
D & = 0 \\
H & = 5 \\
x_d & = 1.8 \\
x_d' & = 0.1 \\
\tau_d & = 10 \\
K_a & = 400 \\
\tau_a & = 0.1
\end{align*}
\]

DFIG:

\[
\begin{align*}
\omega_0 & = 100 \pi \\
H & = 4 \\
\omega & = 100 \pi \\
R_s & = 0.01 \\
R_r' & = 0.02 \\
x_d & = 0.01 \\
x_d' & = 0.01 \\
x_m & = 5
\end{align*}
\]

DFIG controllers:

\[
\begin{align*}
K_{p1} & = 0.1 \\
K_{i1} & = 10 \\
K_{p2} & = 0.1 \\
K_{i2} & = 10
\end{align*}
\]

Suggested controller:

\[
\begin{align*}
K & = 2 \\
K_1 & = 50 \\
K_2 & = 1 \\
\tau & = 0.1
\end{align*}
\]

Test network:

\[
\begin{align*}
X_{11} & = 0.05 \\
X_{12} & = 0.025 \\
X_{44} & = 0.6 \\
X_{12} & = 0.6 \\
V_b & = 1
\end{align*}
\]

REFERENCES


fed induction generator based on the torque limit. IEEE transactions on power systems : a publication of the Power Engineering Society, 31(6), 4575–4583. doi:10.1109/tpwrs.2015.2514240


