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Power System Stability Including Wind Farm with Statcom Based Pi Fractional Controller

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Abstract: In this paper, a new static synchronous compensator (STATCOM) based PI fractional control technique is proposed. The system equations were transformed to the normal form, then, design a fractional order, finally, we propose adaption laws for switching gains. The control objective is to enhance stability and improve the dynamic response of the multi-machine power system including wind farm. Simulations are carried out to show the effectiveness of the proposed method. Small signal stability characteristics of the system are analyzed in presence of changes in reference mechanical torque. By simulation, the proposed method is compared with the conventional PI controller. It is shown that the proposed method has lower spike and shorter reaching time than PI STATCOM.

Keywords: Static synchronous compensator STATCOM, Multi-machine power system, Wind farm, PI Fractional order controller, Adaptive controller

Introduction

Nowadays, enhancement of the dynamic stability of power systems is an important subject of researches (Basler et al). If the damping torque of the generator is not enough, then some fluctuations persist for a long time and may become more considerable. They may have a negative effect on damping of rotor swing. When dealing with power systems angle stability, oscillations damping is very important factor particularly when a fault occurrence.

STATCOM is one of the most significant devices in FACTS technology It is used in parallel compensation, enhancing the transient stability, limiting the low frequency oscillations ...etc. Designing a proper controller is effective in STATCOM operation. It is also added to power system to exchange reactive power and to inject active power, which will further enhance damping of oscillations. This makes new challenges for power system engineers; voltage control across the network, as well as the ephemeral fluctuations in power frequency. To reduce the adverse effects of fluctuations and improve dynamic performance, the system has to be imposed under additional signals. One of the cost effective approaches is to connect a feedback controller to the reference voltage input in order to insert an additional signal generator to cause the oscillations damping. It is known as the power system stabilizer, Basler et al.(2005), Golpira et al. (2015), Yu et al.(2015). During last decade, many studies have been done on the usage of a STATCOM in power systems, research of optimal placement STATCOM, coordination STATCOM and the use of more effective methods in STATCOM design, Padiyar et al.(2008), Kundur (1994), El-Zonkoly et al.(2009), Tapia et al.(2012), Abdelaziz et al.(2006), R. Latha et al.(2018). In power systems, the perturbation and uncertainty are inevitable so that robust methods must be applied. Among these methods, the fractional PID should be noted which have superior benefits than the PID method in its degree of freedom and robustness, Chaib et al.(2015) However, it has lower resistance against disturbances compared with non-linear controllers, i.e. the sliding mode controller. The design of fractional order controllers in different fields has been studied by many researchers, Delavari et al.(2010), (2012), Faieghi et al.(2012). Several comparative studies have shown that fractional PI controllers are superior to conventional PI controllers, Podlubny et al.(1998), Cao et al.(2011), Li et al.(2013), Delavari et al. (2010), (2015), Wang et al.(2009), Petru et al.(2002). Beside the PI controllers, the fractional calculus is used for improving other type of controllers, Delavari et al. (2010), (2013), Calderon et al.(2006), Efe et al.(2010). Industrial applications of fractional order controllers are explained in Chathoth et al.(2015), Mehmood et al.(2015) and Monje et al.(2010). Some novelties in our contribution:

- A new fractional order PI controller is proposed and thus more degrees of freedom is created,
- Stability of the proposed method has been proved,
- Stability of the proposed controller, by using the optimization of GA, has been proved.

This paper is organized as follows. Section II presents the multimachine power system including wind farm being studied and the dynamic model of a synchronous generator is described. Section III presents the mathematical model of the STATCOM. Section IV presents the model of wind turbine. Section V discribe the synchronous generator modelling. The design of the proposed STATCOM with Adaptive Fractional Order AFOPI Controller is presented in section V. Section VI contains simulation results of the proposed method. Conclusions are drawn in section VII. The controller is validated using nonlinear model simulation.

Multi-Machine Power System Including Wind Farm Being Studied

A two-area multi-machine power system consisting of four synchronous generators with loads is shown in Figure. 1. The two areas are identical, and each includes two generators equipped with fast acting excitation systems.

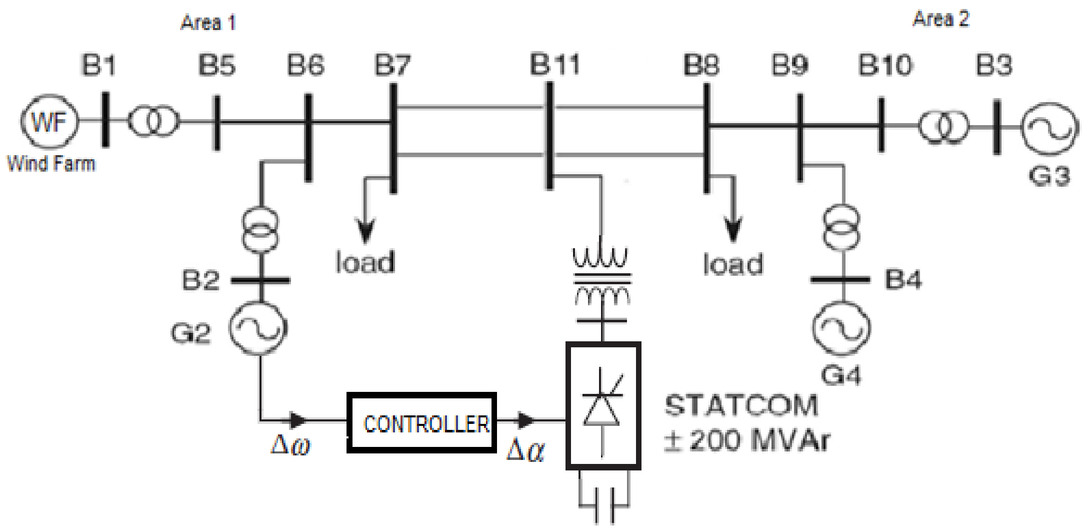

Figure. 1. Single diagram of a 4-Machines 11-Bus System

STATCOM is connected to generator 2. The wind farm is considered as generator 1. This two-area system has been designed to study low-frequency electromechanical oscillations in large interconnected power systems. It has also been modified to include FACTS devices for studying the inter area mode damping improvement. In the present study, a STATCOM is installed at bus 11, as shown in Fig.1. The capacity of capacitors installed at bus 7 is changed from 187 to 200 MVAr while the capacity of capacitors installed at bus 8 is changed from 187 to 180 MVAr. These capacitors, together with STATCOM, will maintain the load voltage profile to close to 1 p.u. The system being studied is simulated by MATLAB software.

STATCOM Modelling

The STATCOM is modeled using the model described in (Podlubny). This model is essentially a controllable voltage source. The state variables of a system of multi machine with STATCOM are amended as follows:

$$\Delta X = \left[\Delta X_1^{T} \quad \Delta X_2^{T} \quad \ldots \quad \Delta X_m^{T}\right]^{T} \tag{1}$$

Where: $\Delta X_i = \left[\Delta\delta_i \quad \Delta\omega_i \quad \Delta E'_{qi} \quad \Delta E'_{di} \quad \Delta E_{fd_i} \quad \Delta V_{R_i} \quad \Delta R_{F_i} \quad \Delta V_{s_i} \quad \Delta X_{s_2} \quad \Delta X_{s_3} \quad \Delta V_{sc}\right]^{T}$ for the i^{th} generator from which the STATCOM controller receives the auxiliary input signal $(\Delta\omega)$ and the state variable $\Delta X_i = \left[\Delta\delta_i \quad \Delta\omega_i \quad \Delta E'_{q_i} \quad \Delta E'_{d_i} \quad \Delta E_{fd_i} \quad \Delta V_{R_i} \quad \Delta R_{F_i} \quad \Delta V_{s_i}\right]^{T}$ for the $i = 1,2,3,\ldots,(m-1)$ remaining generators.

It is assumed that the STATCOM is connected to a load j^{th} busbar, the active and reactive power equations of a STATCOM can then be obtained as follows:

$$P_{sc} = |V_{sc}|^2 G_{sc} - |V_{sc}||V_j|\left[G_{sc}\cos(\delta_{sc}-\theta_j) + B_{sc}\sin(\delta_{sc}-\theta_j)\right] \tag{2}$$

$$Q_{sc} = -|V_{sc}|^2 B_{sc} - |V_{sc}||V_j|\left[G_{sc}\sin(\delta_{sc}-\theta_j) - B_{sc}\cos(\delta_{sc}-\theta_j)\right] \tag{3}$$

Where $V_{sc}\angle\delta_{sc}$ the reverse voltage (AC) to the output of the STATCOM and $Y_{sc} = G_{sc} + jB_{sc}$. G_{sc} and B_{sc} are respectively the conductance and susceptance of the transmission line between the load bus bar and STATCOM.
Therefore, the linearization of active and reactive power equations of the j-th load bus bars can be represented by equation (4). Here, voltage amplitude V_{sc} and phase angle δ_{sc} are taken to be the state variables. The power flow equations $i = m+1, m+2, \ldots, (n-1)$ for other load bus are not affected:

$$\begin{bmatrix} \Delta P_j \\ \Delta Q_j \\ \Delta P_{sc} \\ \Delta Q_{sc} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial\theta_j} & \frac{\partial P_j}{\partial V_j} & \frac{\partial P_j}{\partial\delta_{sc}} & \frac{\partial P_j}{\partial V_{sc}} \\ \frac{\partial Q_j}{\partial\theta_j} & \frac{\partial Q_j}{\partial V_j} & \frac{\partial Q_j}{\partial\delta_{sc}} & \frac{\partial P_j}{\partial V_{sc}} \\ \frac{\partial P_{sc}}{\partial\theta_j} & \frac{\partial P_{sc}}{\partial V_j} & \frac{\partial P_{sc}}{\partial\delta_{sc}} & \frac{\partial P_{sc}}{\partial V_{sc}} \\ \frac{\partial Q_{sc}}{\partial\theta_j} & \frac{\partial Q_{sc}}{\partial\theta_j} & \frac{\partial Q_{sc}}{\partial\delta_{sc}} & \frac{\partial Q_{sc}}{\partial V_{sc}} \end{bmatrix} \begin{bmatrix} \Delta\theta_j \\ \Delta V_j \\ \Delta\delta_{sc} \\ \Delta V_{sc} \end{bmatrix} \tag{4}$$

Wind Turbine Modelling

The captured mechanical power (in W) by a Wind turbine (WT) can be written by:

$$P_{mw} = \frac{1}{2}\rho_w.A_{rw}.V_w^3.C_{pw}(\lambda_w,\beta_w) \tag{5}$$

Where ρ_w is the air density (kg/m^3), A_{rw} is the blade impact area (m^2), V_w is the wind speed (m/s), and C_{pw} is the dimensionless power coefficient of the WT. The power coefficient of the WT C_{pw} is given by:

$$C_{pw}(\Psi_{kw},\beta_w)=c_1\left(\frac{c_2}{\Psi_{kw}}-c_3.\beta_w-c_4.\beta_w^{c_5}-c_6\right)\exp\left(-\frac{c_7}{\Psi_{kw}}\right) \tag{6}$$

$$\frac{1}{\Psi_{kw}}=\frac{1}{\lambda+c_8.\beta_w}-\frac{c_9}{\beta_w^3+1} \tag{7}$$

$$\lambda_w=\frac{R_{bw}.\omega_{bw}}{V_w} \tag{8}$$

Where ω_{bw} is the blade angular speed (rad/s), R_{bw} is the blade radius (m), λ_w is the tip speed ratio, β_w is blade pitch angle (degrees), and c1-c9 are the constant coefficients for power coefficient C_{pw} of the studied WT. The power coefficients of the WT can be referred to . The cut-in, rated, and cut-out wind speeds of the studied WT are 4, 15, and 24 m/s, respectively. When wind speed V_w is lower than the rated wind speed of the WT (V_{wrated}), βw = 0°. When $V_w > V_{wrated}$, the pitch-angle control system of the WT activates and the pitch angle of the WT (β_w) increases.

Some of the machine inductances are functions of the rotor speed, whereupon the coefficients of the state-space equations (voltage equations), which describe the behavior of the induction machine, are time-varying (except when the rotor is at stand-still). A change of variables is often used to reduce the complexity of these state-space equations. There are several changes of variables which are used but there is just one general transformation. This general transformation refers to the machine variable to a frame of reference, which rotates at an arbitrary angular velocity ω_g . In this reference frame the machine windings are replaced with some equivalent windings.

The d-q axis equivalent circuit model of the studied wind DFIG can be expressed by:

$$\begin{bmatrix}v_{sd}\\v_{sq}\end{bmatrix}=\begin{bmatrix}R_s&0\\0&R_s\end{bmatrix}\begin{bmatrix}i_{sd}\\i_{sq}\end{bmatrix}+\frac{d}{dt}\begin{bmatrix}\varphi_{sd}\\\varphi_{sq}\end{bmatrix}-\begin{bmatrix}0&-\frac{d\theta_s}{dt}\\\frac{d\theta_s}{dt}&0\end{bmatrix}\cdot\begin{bmatrix}\varphi_{sd}\\\varphi_{sq}\end{bmatrix} \tag{9}$$

$$\begin{bmatrix}v_{rd}\\v_{rq}\end{bmatrix}=\begin{bmatrix}R_r&0\\0&R_r\end{bmatrix}\begin{bmatrix}i_{rd}\\i_{rq}\end{bmatrix}+\frac{d}{dt}\begin{bmatrix}\varphi_{rd}\\\varphi_{rq}\end{bmatrix}-\begin{bmatrix}0&-\frac{d\theta_r}{dt}\\\frac{d\theta_r}{dt}&0\end{bmatrix}\cdot\begin{bmatrix}\varphi_{rd}\\\varphi_{rq}\end{bmatrix}$$

$$\begin{bmatrix}\varphi_{sq}\\\varphi_{rq}\end{bmatrix}=\begin{bmatrix}L_s&M\\M&L_r\end{bmatrix}\cdot\begin{bmatrix}i_{sq}\\i_{rq}\end{bmatrix}$$

$$\begin{bmatrix}\varphi_{sd}\\\varphi_{rd}\end{bmatrix}=\begin{bmatrix}L_s&M\\M&L_r\end{bmatrix}\cdot\begin{bmatrix}i_{sd}\\i_{rd}\end{bmatrix} \tag{10}$$

Where:

R_s, R_r, L_s, L_r are the resistances and inductances of the stator and rotor windings, M is the main inductance.

$v_{sd}, v_{sq}, v_{rd}, v_{rq}, i_{sd}, i_{sq}, i_{rd}, i_{rq}, \varphi_{sd}, \varphi_{sq}, \varphi_{rd}, \varphi_{rq}$ are the d and q-components of the space phasors of the stator and rotor voltages, currents, and flux.

Currently, in wind turbine applications the back-to-back voltage source converter (VSC) is mainly used. This topology comprises a double conversion from AC to DC and then from DC to AC. Both converters can operate in rectifier or inverter mode and therefore a bi-directional power flow can be achieved. A voltage source converter can be implemented in several ways: six-step, pulse amplitude modulated (PAM) or pulse width modulated (PWM). Moreover, the implementation of a PWM VSC may be realized by three methods: harmonic elimination, “sinusoidal” PWM or space vector strategy (SV-PWM).

Synchronous Generator Modelling

The detailed nonlinear model of a synchronous generator is a sixth order model. However, this model is usually reduced to a generalized one-axis nonlinear third order model. The equations describing a third order model of a synchronous generator, for j-th generator, can be written as:

$$Y_{sc} \quad Y_{\max} \quad Y_{\min}$$

$$\begin{aligned} \frac{d}{dt}\omega &= -\frac{K_D}{2H}(\omega(t)-\omega_0)+\frac{\omega_0}{2H}(P_m - P_C(t)) \\ \frac{d}{dt}E_q^{'}(t) &= \frac{1}{T_{d0}^{'}}(E_F(t)-E_q(t)) \end{aligned} \tag{11}$$

Where :

$$\begin{aligned} E_q(t) &= \frac{x_d}{x_d^{'}}E_q^{'}(t)-\frac{x_d - x_d^{'}}{x_d^{'}}V_S\cos(\delta(t)) \\ E_F(t) &= k_C u_F(t) \\ P_C(t) &= \frac{V_S E_q(t)}{X_d}\sin(\delta(t)) \end{aligned} \tag{12}$$

Where: $\delta_j(t)$ is the rotor angle of the j-th generator (radians), $\omega_j(t)$ is the speed of the rotor of the j-th generator (radian/sec), ω_{0j} is the synchronous machine speed of the j-th generator (radian/sec), K_{Dj} is the damping constant of the j-th generator (pu), H_j is the inertia constant of the j-th generator (sec), $P_{mj}(t)$ is the mechanical input power of the j-th generator (pu), $P_{ej}(t)$ is the active electrical power delivered by the j-th generator (pu), $E_{qj}(t)$ is the EMF of the q-axis of the j-th generator (pu), $E_{qj}^{'}(t)$ is the transient EMF in the q-axis of the j-th generator (pu), $E_{Fj}(t)$ is the equivalent EMF in the excitation winding of the j-th generator (pu), $T_{d0j}^{'}$ is the d-axis transient short circuit time constant of the j-th generator (sec), k_{Cj} is the gain of the excitation amplifier of the j-th generator, $u_{Fj}(t)$ is the control input of the excitation amplifier with gain k_{Cj} , x_{dj} is the d-axis reactance of the j-th generator (pu), $x_{dj}^{'}$ is the d-axis transient reactance of the j-th generator (pu), X_{dj} is the total direct reactance of the system (pu), $X_{dj}^{'}$ is the total transient reactance of the system (pu), and V_S is the infinite bus voltage (pu).

Design of the Proposed STATCOM with Adaptive Fractional Order AFOPI Controller

The voltage control model is completed at bus 10 by the mathematical equation that depicts the reactive power provided to the STATCOM node Abdelaziz et al.(2006):

$$Q_{sc} = -B_{sc}V_{10}^2 \tag{13}$$

Where : B_{sc} indicate the susceptance.

The FOPI controller, depicted in figure 2, is used to determine the value of either B_{sc} or Y_{sc} .

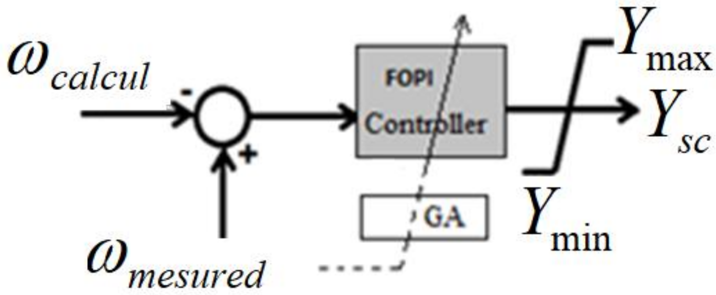

Figure 2. STATCOM equipped with a FOPI controller

Thus, it becomes crucial to develop an efficient approach to adjusting FOPI controller settings to optimize power system stability control. The Genetic Algorithm (GA) is built on the principles of natural selection and genetics, functioning as a global search tool. The initial step in tuning the FOPI controller parameters for the GA application is to consider that each FOPI controller has only one input.Table (I) presents the GA parameters during the scaling factor adjustment phase. Figure.3. Shows the suggested algorithm flowchart

Table 1. The scaling factors tuning the stage with the GA parameters

Variable number	9
Every variable's gene number	3
length of a chromosome	27
Size of the population	54
Number of generation	50

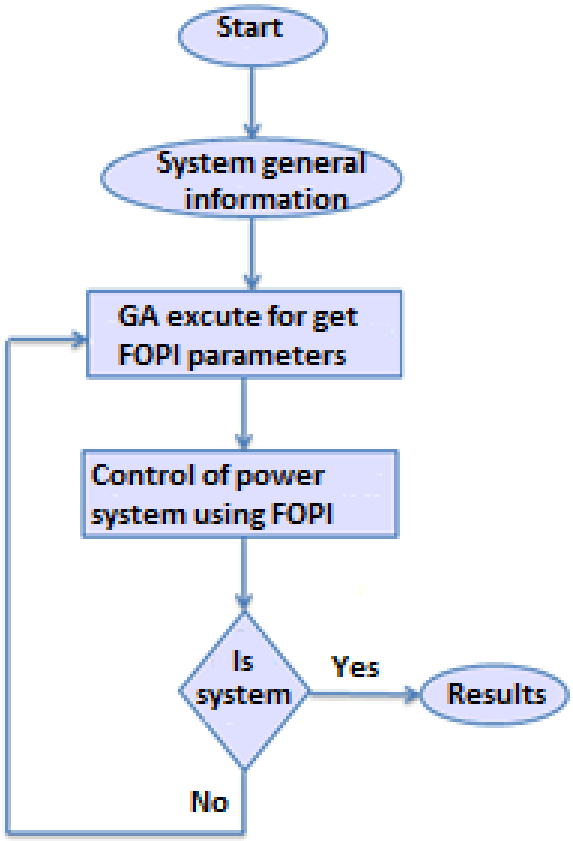

Figure 3. An algorithm diagrams of GA

The adaptive feedback control law, as mentioned in reference, is used to formulate the integer adaptive PI controller.

$$
\begin{aligned}
& u(t) = -k_c\left[k_1(t)e(t) + \int_0^t k_2(\tau)e(\tau)d\tau \right] \\
& k_1(t) = k_p(t) + \alpha_1 k_i(t) \\
& k_2(t) = \alpha_2 k_i(t) \\
& k_p(t) = e^2(t) \\
& k_i(t) = \int_0^t e(\tau)^2 d\tau \\
& e(t) = y(t) - r(t)
\end{aligned} \tag{14}
$$

Where y is the output signal, u the control input and r the reference signal. k_c, α_1 and α_2 are positive constants. The new control algorithm is obtained using the fractional-inaction of the integral operator $1/s$ as follow:

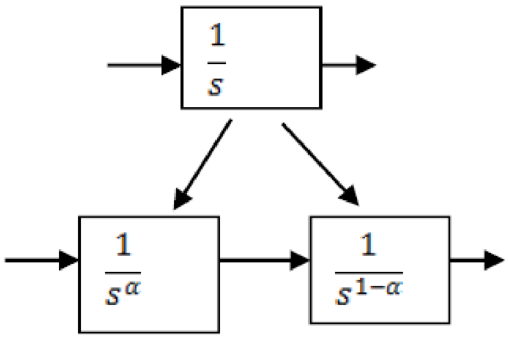

Figure 4. Fractionalization as an integral operator

$$
\begin{aligned}
& u(t) = -k_c\left[k_1(t)e(t) + l^{1-\lambda}\left\{ l^{\lambda}\left\{ k_2(t)e(t) \right\}\right\}\right] \\
& k_1(t) = k_p(t) + \alpha_1 k_i(t) \\
& k_2(t) = \alpha_2 k_i(t) \\
& k_p(t) = e^2(t) \\
& k_i(t) = l^{1-\lambda}\left\{ l^{\lambda}\left\{ e^2(t) \right\}\right\} \\
& e(t) = y(t) - r(t)
\end{aligned} \tag{15}
$$

Figure 5 shows the suggested adaptive fractional PI controller.

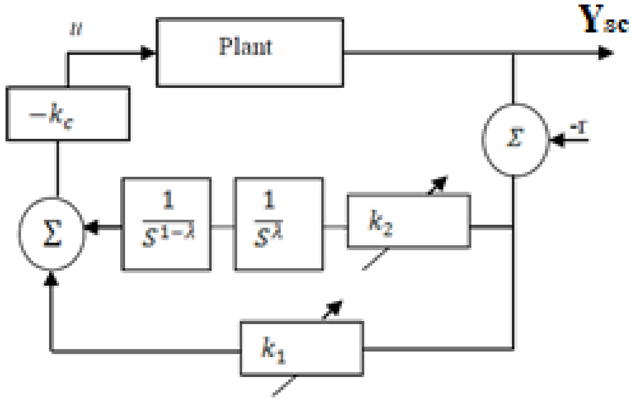

Figure 5. The proposed adaptive PI control system (AFOPI)

Results and Discussion

In this section, the simulation results of the proposed controller are obtained for a four-machine power system with the wind farm intergration under MATLAB-SIMULINK environment. The classic PI control and adaptive fractional PI control based STATCOM are compared in terms of bus voltages, line power, difference between rotor angle deviation of machine of wind turbine and machine 2, speed of the machines, terminal voltages of machines. The power coefficient and tip speed ration of the wind turbine is given by the Figure 6.

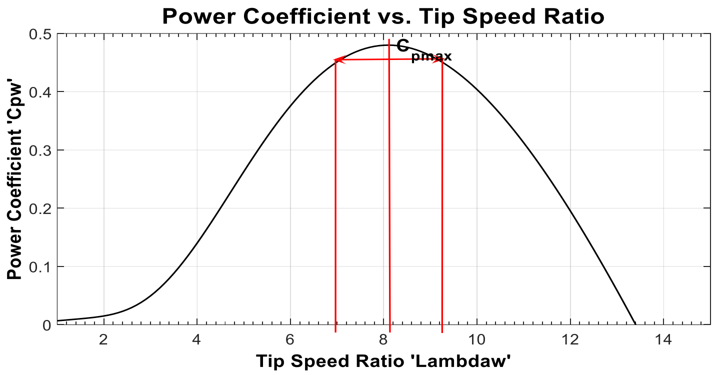

Figure 6. The power coefficient of the wind turbine

The Figure 7 shown the wind turbine characteristics in which the pitch angle is equal 0.

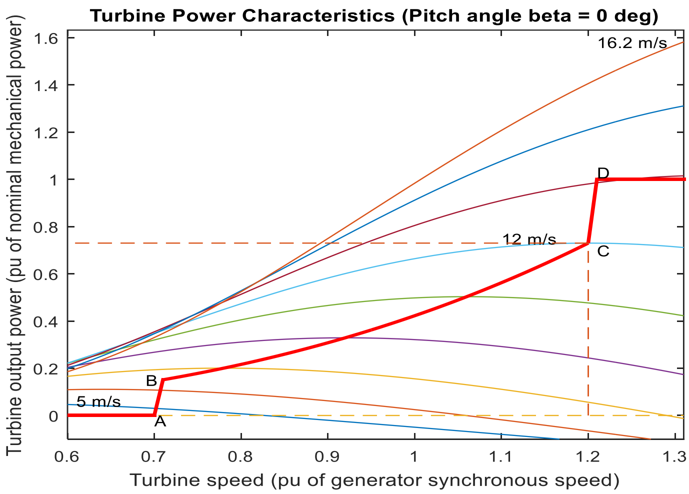

Figure 7. The power coefficient of the wind turbine

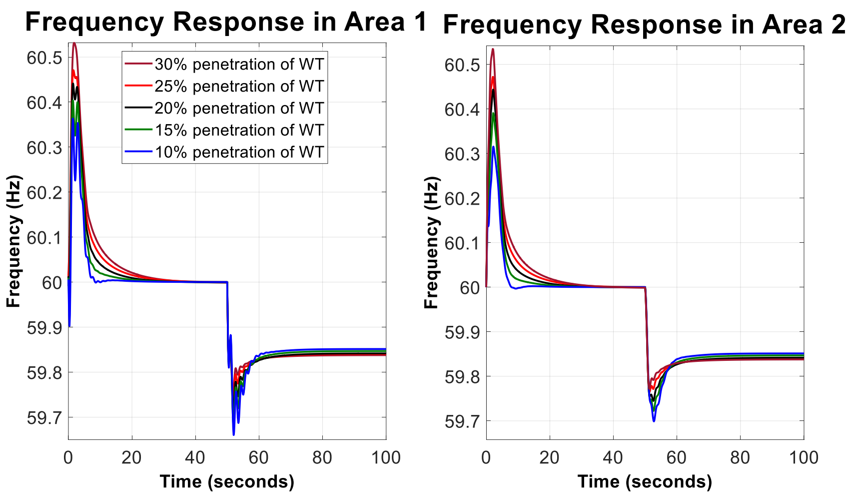

Figure 8. The frequency response

The results shown in figure 9 that, compared with different percentage penetration active power of the wind turbine, test system enhances the voltage profile, decreases active and reactive power losses, and increases power system stability in the power system. The frequency and the electrical power using the proposed controller have shown in Figure 10. It can be noted that the proposed controller decreases settling time of the load angle and increases the rate of damping of the frequency and the electrical power of the generators. As also shown in the figures, the suggested control method is able to make damping driving less than 2 to 3 seconds.

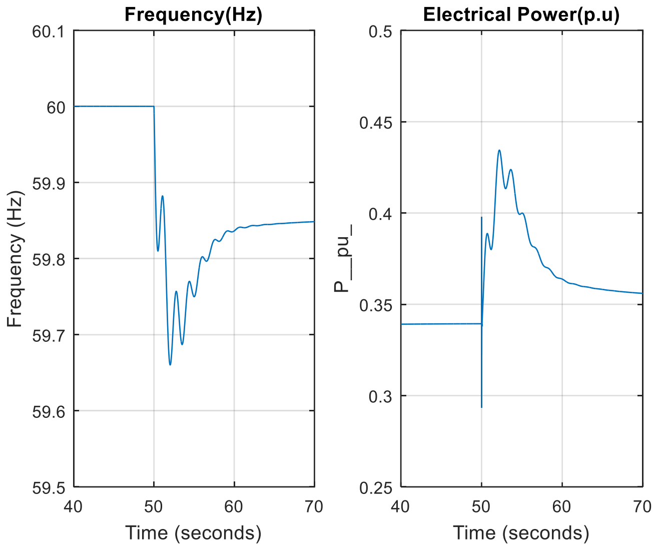

Figure 10. The frequency and the electrical power

The rotor speed and the electromagnetic torque of four machines is very high by using the proposed controller and the machines reach the desired speed in smaller time. The responses are illustrated in Fig.11.

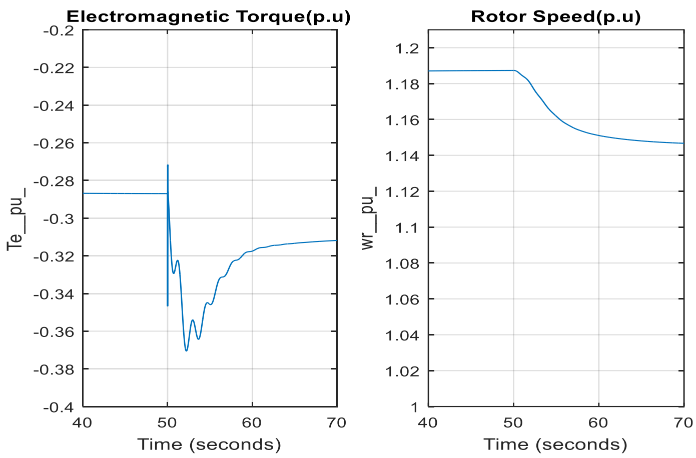

Figure 11. The electromagnetic torque and the rotor speed

By allocating the wind turbine integration and the STATCOM with the proposed controller, system losses are decreased, voltage regulation is enhanced, voltage deviation is reduced, and transient stability is improved.

Conclusion

Power systems parameters vary due to noise, disturbance and load fluctuation. Power system stabilizer (PSS), installed in the Automatic Voltage Regulator (AVR) of a generator, can improve power system stability. The PSS has excellent cost performance compared to other power system modifications or additions. In this paper, the STATCOM based an adaptive fractional PI controller for power system including wind farm is proposed. Simulations shows that the proposed controller reduces the amount of overshoot and the load angle meetings of each generator and increases in speed damping of the system. Results show that the proposed controller has superior accuracy and speed.

Scientific Ethics Declaration

* The authors declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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