Indonesian Journal of Electrical Engineering and Computer Science
Vol. 4, No. 2, November 2016, pp. 341 ~ 353
DOI: 10.11591/ijeecs.v4.i2.pp341-353

A Robust Control with the Combination of Fuzzy and SMC to Stabilize the Power System

Mohammadreza Barzegaran*[1], Sana Tajvidi[2]
[1]University of Tehran, Enghelab St., Tehran, Iran
[2]Amirkabir University of Technology, Hafez St., Tehran, Iran
*Corresponding author, e-mail: f.mirzaie@hotmail.com

Abstract

Common power system stabilizer (CPSS), fuzzy power system stabilizer (FPSS) and sliding mode controller (SMC) are common controllers which are used in controlling single machine infinite bus (SMIB) power systems. Each of these controllers has disadvantages. CPSS is not robust enough to stabilize the power system perfectly. SMC is more robust than CPSS but in the presence of big uncertainties it is unable to stabilize power system. FPSS is enough robust in the presence of big uncertainties, but it causes chattering when high switching gain is needed. The goal of this paper is to present a robust controller for a single machine infinite bus (SMIB). The proposed controller is a direct fuzzy controller assisted with a sliding mode controller. The simulation shows clear positive effect and validity of the method in convergence, time and accuracy.

Keywords: *power system stabilizer, fuzzy controller, sliding mode controller, synchronous machine*

1. Introduction

Development in the field of wind turbines to produce electricity has begun since 1970. The first modern turbine has joined to network since 1980. Spreading the use of wind energy and electricity causes wind turbines connected to Double Fed Induction Generator (DFIG) to be widely used. These generators are widely used because of their characteristics in variable wind velocities profile. Using power stations which are designed for variable wind velocity profile is dominant over power stations of constant wind velocity. Although wind power stations with constant wind velocity can be directly connected to the network, larger domain of energy can be covered by wind stations of variable wind velocity profile and experiences less mechanical stress and produces less acoustic noise. Squirrel cage induction generators are often used in energy systems of constant wind velocity which are connected directly to the network. These systems are called Fixed Speed Wind Electric Conversion Systems or simply WECS. In these systems, the method of changing number of machine poles is utilized in order to make the system efficient is the range of minimum and maximum possible wind velocity profile. In this case the system is economically advantageous, but as it is covering whole wind velocity profile, whole wind energy is not utilized perfectly. Today, power electric developments made control possible and economic in various velocities. In this paper, DFIG with various velocity is utilized, which has important features in various wind velocity profile [1-3].

The graph illustrating momentum versus velocity looks like stairs. Moreover, voltage and output power is swinging as wind velocity flactuate [4-5]. In this system, capacitor bank must be utilized to provide required reactive power as the reactive power controller is not embedded. It is noteworthy that in order to control rotor speed between two steps of number of poles changes, a blade pitch angle controller is used in the turbine.

Direct drive control techniques are widely used because of simplicity, fast dynamics and stable efficiency. The idea of Direct Torque Control (DTC) presented in 1986. DTC for inductive drives and DFIG are widely noted by researchers in various articles [6]. Recently, researchers presented direct active and reactive Power Control (DPC) inspired by DTC for 3 phase rectifiers and DFIG [7]. The purpose of DPC in DFIG is the direct, independent control of power in active and reactive stators in the minimum time with minimum ripple.

Received September 11, 2016; Revised October 10, 2016; Accepted October 22, 2016

Equations of bipolar rotor and stator voltage vectors of DFIG which is transferred to rotating reference of rotor are presented as (1) and (2). ω_r and ω_s are angular velocities of rotor and stator.

$$V_s = R_s I_s + \frac{d\varphi_s}{dt} + j\omega_r\varphi_s \tag{1}$$

$$V_r = R_r I_r + \frac{d\varphi_r}{dt} \tag{2}$$

In the equation, I_s I_r V_s V_r φ_s φ_r R_s R_r are vectors of current, voltage, flux and stator and rotor resistance, in the rotating reference of rotor respectively. Rotor and stator flux vectors are presented in (3).

$$\begin{aligned} \varphi_s &= L_s I_s + L_m I_r \\ \varphi_r &= L_r I_r + L_m I_s \end{aligned} \tag{3}$$

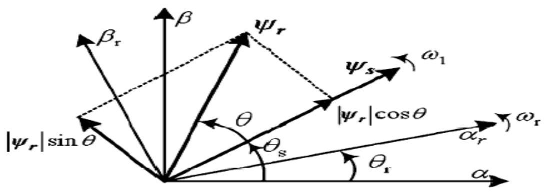

Figure 1. Rotor and Stator Flux Vectors in Fixed Rotating Reference of the Rotor [8]

here, L_m, L_r and L_s are reciprocal and self inductance of rotor and stator. Based on equation (3), rotor and stator currents are calculated as (4) [9].

$$\begin{aligned} I_s &= \frac{L_r\varphi_s - L_m\varphi_r}{L_s L_r - L_m^2} = \frac{\varphi_s}{\sigma L_s} - \frac{L_m\varphi_r}{\sigma L_s L_r} \\ I_r &= \frac{L_s\varphi_r - L_m\varphi_s}{L_s L_r - L_m^2} = \frac{\varphi_r}{\sigma L_r} - \frac{L_m\varphi_s}{\sigma L_s L_r} \\ \sigma &= \frac{(L_s L_r - L_m^2)}{L_s L_r} \end{aligned} \tag{4}$$

Active and reactive powers injected to generator from the network are calculated as (5) and (6).

$$P_s = 1.5\, V_s . I_s \tag{5}$$

$$Q_s = -1.5\, V_s * I_s \tag{6}$$

which (*) and (.) represent vector product and dot product of current vector and stator voltage vector respectively. Replacing equations (1) and (2) in equation (3) we have:

$$P_s = -K_\sigma \omega_1 |\varphi_s||\varphi_r| sin\theta \tag{7}$$

$$K_\sigma = 1.5 \frac{L_m}{(\sigma L_r L_s)} \tag{9}$$

θ is the angle between rotor and stator flux vector which is shown in Figure 1. If network voltage is fixed and balanced and rotor velocity is constant in sampling time, neglecting rotor resistance, domain and angular velocity of the stator will be unchanged. Therefore, differentiating equation of (7) and (8), there is:

$$\frac{dP_s}{dt} = -K_\sigma \omega_1 |\varphi_s| \frac{d(|\varphi_r| sin\theta)}{dt} \tag{9}$$

$$\frac{dQ_s}{dt} = K_\sigma \omega_1 |\varphi_s| \frac{d(\,|\varphi_r| cos\theta\,)}{dt} \quad (10)$$

Based on equations (9) and (10), if ω_1 and $|\varphi_s|$ are unchanged, variation of active and reactive power is controllable by using rotor flux terms$|\varphi_r|sin$ and $|\varphi_r|cos$. Figure 1 illustrates these terms. Neglecting rotor resistance, there is:

$$\frac{d|\varphi_r|}{dt} = V_r - R_r I_r \simeq V_r \quad (11)$$

Based on (11) rotor flux changes are controlled by rotor voltage. Movement of rotor flux is in the direction of rotor voltage vector. Velocity of this movement is proportional with rotor voltage amplitude. Stator flux is calculated through (12) in each sampling time.

$$\varphi_s = \int (\, V_s - R_s I_s \,) dt \quad (12)$$

Effect of each voltage vector on active and reactive power is calculable if stator flux position is known. The most effective rotor voltage vectors for reducing power deviation from reference values are presented using double level invertors capable of producing 8 voltage vectors in reference 6 [7, 9].

2. Controller Design and Modelling

In order to design a controller for a system, first of all, there should be a vivid picture of the system. Inputs and outputs to the system should be categozied and order of the system should be analyzed. If the model of the system is unknown, model independent controllers should be selected. In this section, aerodynamic model of the wind turbine, shaft and the gearbox is modeled. Then, the proposed controlled is described.

2.1. Modelling of DFIG Wind Turbine

Wind turbine is a system of blades which receives wind energy and changes that into usable mechanical energy. Kinetic energy swept by wind turbine rotor is shown in (13).

$$P_m = \frac{1}{2}\pi\rho R^2 C_p(\lambda\,,\beta) v^3 \quad , \quad \lambda = \frac{R\omega_t}{v} \quad (13)$$

here, P_m is the kinetic energy swept by the rotor, ρ, air density and R is the swept area of the rotor exposed to wind v is the wind velocity and C_p, β and λ are respectively coefficient factor, blade pitch angle and firm's velocity factor. ω_t Represents the turbine angular velocity. In the modelling of axis, gearbox and DFIG, euations and relations should be written in a specific refrence frame. The reference frame is a rotating with the synchronous speed in the axis (d.q) of stator flux. In order to use the refrence frame, non-linear state space relations assisted with Park transformation is used [12]. Lee derivative is used to linearize inouts and outputs.

If $h(x)(R^n \to \mathrm{R})$ is a scalar field and $f(x)(R^n \to R^n)$ is a vector field, Lee derivative of scalar field $h(x)$ is defined compared to vector field $f(x)$ as shown is (14).

$$L_f h = \nabla h f = \frac{\partial h}{\partial x} f(x) \quad (14)$$

besides, active and reactive power of the stator are described in (15) as separate systems.

$$y = \frac{3}{2}[u_{ds} \quad u_{qs}] \begin{bmatrix} x_1 & x_1 \\ x_2 & x_2 \end{bmatrix} \qquad y = [P_s \quad Q_s] \quad (15)$$

$$\dot{y}_1 = \frac{\partial h}{\partial x_1}(\dot{x}_1) = \frac{\partial h}{\partial x}(f(x_1) + (g_{11} + g_{12})u_r + (d_{11} + d_{12})u_s + e_{11}T_L) = L_f h(x_1) + L_{g12} h(x_1) u_{rq} \quad (16)$$

$$\dot{y}_2 = \frac{\partial h}{\partial x_1}(\dot{x}_2) = \frac{\partial h}{\partial x}(f(x_2) + (g_{21} + g_{22})u_r + (d_{21} + d_{22})u_s + e_{21}T_L) = L_f h(x_2) + L_{g21} h(x_2) u_{rd} + L_{d21} h(x_2) u_{sd} \quad (17)$$

According to (15) and (14), system equations can be shown as (16) and (17). Equations (16) and (17) can be rewritten as (18), assuming (19), (20) and (21).

$$\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} = \begin{bmatrix} L_f h(x_1) \\ L_f h(x_2) \end{bmatrix} + D_r \begin{bmatrix} u_{rd} \\ u_{rq} \end{bmatrix} + G_s \begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} \quad (18)$$

$$\mathrm{L_f h(x_1)} = (489.9)(\, a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + a_{14}x_2x_5 + a_{15}x_4x_5) \quad (19)$$

$$\mathrm{L_f h(x_2)} = (489.9)(\, a_{21}x_1 + a_{22}x_2 + a_{23}x_4 + a_{24}x_3x_5 + a_{25}x_1x_5) \quad (20)$$

$$D_r = \begin{bmatrix} 0 & L_{g12} h(x_1) \\ L_{g21} h(x_2) & 0 \end{bmatrix} \;,\; G_s = \begin{bmatrix} 0 & 0 \\ L_{d21} h(x_2) & 0 \end{bmatrix} \quad (21)$$

The equation (18) describes system and can be used to design a controller based on it. In the next section the proposed controller is described.

2.2. Controller

In this study, the proposed controller is a combination of a fuzzy controller and a sliding mode controller utilized together to controller the wind turbine. The following description illustrates at first fuzzy controller and then sliding mode controller.

In order to stabilize DFIG, PID controllers are the most utilized controllers. PID controllers are usefull in constant speed wind turbines. In variable speed wind, PID controller might cause uneffecient control for stability or even instability in DFIG. This happens beacuase PID coefficients are optimized for a single condition and that is a specific constant wind speed. In this study, it is assumed that there is variable wind speed and controllers should be able to stabilize DFIG in this condition. Fuzzy controller and SMC is designed in order to stabilize DFIG in this condition.

2.2.1. Fuzzy Controller

Fuzzy controllers are based on series of rules that generates control signal in various conditions. These rules devide the continuous domain of the controller into some descrete domains. This logic can be combined with some other controllers. A PID controller can be utilized as a fuzzy controller if P, I and D coefficients are changeable due to the rules.
In this study, a simple PI controller is utilized to stabilize DFIG. This controller works fine while wind speed is constant. P and I coefficients in the PI controller are not constant and varies with the wind speed. The wind speed is assumed to vary between 5 to 60 meters per second. The fuzzy rule discretize wind speed makes a subspace for each 5 meters per second increase in wind speed. In each subspace P and I coefficients are calculated. These coefficients are tabulated in a lookup table and the PI controller uses the table to utilize relevant coefficents.

As speed increases, the torque increases firstly and then descreases. So in a specific speed, pitch angle should be regulated such that the maximum torque is obtained. The fact that in a constant pitch angle, increment in wind speed causes increment in torque and then decrtement in it, is one of the facts that is used in fuzzy rules.

On the other hand, increment in wind speed causes increment in fluctuation amplitude of wind speed. So in higher wind speed, P coefficient should be increased. This is the second fact that is utilized in fuzzy rules.

Besides, increment in wind speed causes decrement in frequency of fluctuation of wind speed. So in higher wind speed, I coefficient should be descrised. This is the third fact that is utilized in fuzzt rules.

Figure 2 Illustrates fuzzy PI controller which is used in the study. As it is obvious, the coefficinets of the PI controller is selected based on specific rules.

2.2.2. Sliding Mode Controller

Sliding Mode controller is one of non-linear controllers which can control the system in the presence of structural and non-structural uncertainties. This controller uses a control law capable of fast switching between two control states. This makes system state variables to be on a specific surface called sliding surface. This surface is defined such that the system is controlled if state variables are on the it. In this method, control law is composed of two parts. The first part directs system sate to the sliding surface and the other part is responsible for keeping system state on the sliding surface. Sliding mode controller has other advantages other than robustness against uncertainties, which are insensitivity toward external fluctuations, fast responsiveness and simplicity [8-10].

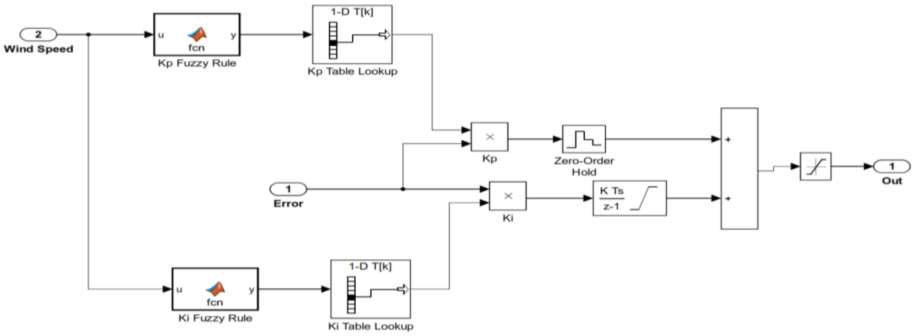

Figure 2. Fuzzy Controller

Sliding mode control is a variable structure control method in which system states are on the predetermined paths (line or switching level) by using control laws and directed toward the specific point using determined dynamic designed by the planner which might be other system dynamic. If the sign of external fluctuation is known, its effect can be eliminated using specific control law. In this case fast switching signal or sign function can be used. The most important features leading to the growth of this method is high accuracy, fast dynamic response, easy applicability and stability in the presence of uncertainty. Sliding mode control is a non-linear control method which guarantees control strategy against uncertainties. Apart from many advantages of the sliding mode controller, there are many problems in this method, the most important of which is high control effort and chattering phenomenon.

In the process of sliding mode controller design, limitation of high frequency switching and uncertainty in the system make system states out of sliding surface and fluctuate around it. We call these fluctuations, chattering which is not a desired phenomenon because it makes increase in control effort and stimulation of model dynamics. Moreover, it can result in high system frequency and system instability. Therefore, many researches are done for elimination of chattering.

Some common methods of reducing chattering are as follows:

a. Efficient design of the discrete part of the control law
b. Using fixed and variable boundary layer
c. Designing integral sliding surface
d. Using fuzzy controller naming as sliding-fuzzy control

Consider the following non-linear SISO system:

$$X^{(n)} = f(x) + bu$$
$$y = x \quad (22)$$

Sliding mode control can be used in systems with limited f and b but they are not exactly specified. Therefore, assume that estimation error of f ,(assume $\hat{f}$), is limited by $(x, \dot{x})$ F □ F as follows:

$$\left|\hat{f} - f\right| \leq F \quad (23)$$

Similarly, b, control gain, is limited as:

$$0 \leq b_{min} \leq b \leq b_{max} \quad (24)$$

Estimation $\hat{b}$ of b is considered as geometry mean. As control input is entered as product in dynamic equation, we can write the range as follows:

$$\hat{b} = \sqrt{(b_{min} b_{max})}$$
$$\beta^{-1} \leq \frac{\hat{b}}{b} \leq \beta \quad (25)$$

Gain range is:

$$\beta = \sqrt{(\frac{b_{max}}{b_{min}})} \quad (26)$$

Sliding model controller is designed to follow preferred curve of xd. control signal u(t) calculated such that closed loop system reaches to sliding surface of s(t) and remains on it. Required control signal of u(t) to be remained of sliding surface, is called $\hat{u}(t)$. sliding surface is defined as follows:

$$s = (\frac{d}{dt} + \lambda)^{n+1} \tilde{x} \quad (27)$$

where, $\tilde{x}$ is defined as the error between x, xd and λ as the constant value with the positive sign. Desired control signal is obtained after a simple algebra calculations putting $\frac{ds}{dt}$ =0.

$$\hat{u} = \frac{1}{\hat{b}}\left(-\hat{f} + \ddot{x}_d - 2\lambda\dot{\tilde{x}} - \lambda^2 \tilde{x}\right) = \frac{1}{\hat{b}}\tilde{u} \quad (28)$$

Conditions for reaching sliding surface and its stability should be specified outside of s(t). Therefore, we define Lyapunov candidate function S^2 V= $\frac{1}{2}$. Ttime derivative of this function is $\dot{V} = \dot{S}S$. Based on Lyapunov rule, u control law should be considered such that, $S\dot{S} \leq -\eta|S|$, switching control law, defined to meet this condition [11].

The problem of this method is the increase in chattering phenomenon which is not desirable because of dynamic stimulation of high frequency model. To overcome this problem, a constant estimation of switching control law is calculated through smoothing discontinuity in the Φ domain and often sign function is replaced with saturation function [11]. Control law is calculated as follows:

$$\hat{u} = \frac{1}{\hat{b}}(\tilde{u} - k sat(\frac{s}{\Phi})) \quad (29)$$

Sliding condition:

$$k \geq \beta(F + \eta) + (\beta - 1)|\hat{u}| \quad (30)$$

Shows that control inequality of k in the surface of s=0 increases as uncertainty in the model and control gain increases. Therefore, (k) term shows uncertainty phenomenon.
According to the purpose of the study, which is to determine control components of the rotor voltage such that active and reactive powers of the stator tracks the desired value sliding model controller is designed such that state variables reach to the following sliding surface:

$$\begin{cases} s_1(t) = P(t) - P_{ref} \\ s_2(t) = Q(t) - Q_{ref} \end{cases} \quad (31)$$

Defining:

$$f^* = \begin{bmatrix} L_f h_1 \\ L_f h_2 \end{bmatrix} + D_s \begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} \quad (32)$$

The following relation is the result of the direct control of the power:

$$\begin{bmatrix}\dot{y}_1\\ \dot{y}_2\end{bmatrix} = \begin{bmatrix}L_f h(x_1)\\ L_f h(x_2)\end{bmatrix} + D_r\begin{bmatrix}u_{rd}\\ u_{rq}\end{bmatrix} + G_s\begin{bmatrix}u_{sd}\\ u_{sq}\end{bmatrix} \tag{33}$$

so we have:

$$\dot{y} = f^*(x) + G_r u_r \tag{34}$$

if the uncertainty of generator's parameters of DFIG is presented in f^* and D_r . following bond is assumed:

$$\left|f_i^*(x) - \hat{f}_i^*(x)\right| \le \delta_i \tag{35}$$

$$G_r = (\mathrm{I} + \Delta)\widehat{G_r} \qquad , \ \left|\Delta_{ij}\right| \le G_{ij} \tag{36}$$

Based on Lyapunov function, control law is defined as follows:

$$V = \frac{1}{2}S^T S > 0 \tag{37}$$

time derivative of V is toward the state path of (37) is as follows:

$$\frac{dV}{dt} = \frac{1}{2}\left(S^T\frac{dS}{dt} + S\frac{dS^T}{dt}\right) = S^T\frac{dS}{dt} = S^T(\hat{f}_i^*(x) + \widehat{G_r}\hat{u}_r - \dot{y}_{ref} \tag{38}$$

control law is defined such that time derivative of V is always negative and S≠ 0. Therefore, control law is defined as follows:

$$u_r = \frac{-1}{\widehat{G_r}}\left[\hat{f}_i^*(x) - \dot{y}_{ref} + Ksgn(S)\right] \tag{39}$$

In this relation:

$$\begin{aligned} &sgn(S) = [sgn(s_1) \quad sgn(s_2)]\\ &sgn(s_i) = \begin{cases}+1 & if \quad s > 0\\ -1 & if \quad s < 0\end{cases}\\ &K = \begin{bmatrix}\eta_1|s_1(t)|^{a1} & 0\\ 0 & \eta_2|s_2(t)|^{a2}\end{bmatrix}\end{aligned} \tag{40}$$

In order to have stable sliding surface, $\frac{dV}{dt} < 0$ is necessary. the stability is guaranteed considering following conditions. Therefore, if $sgn(s_1) > 0$ and $sgn(s_2) > 0$ then it is:

$$\frac{dV}{dt} = \underline{S}^T\frac{d\underline{S}}{dt} = -S^T\begin{bmatrix}\eta_1|s_1(t)|^{a1} & 0\\ 0 & \eta_2|s_2(t)|^{a2}\end{bmatrix}\begin{bmatrix}sgn(s_1)\\ sgn(s_2)\end{bmatrix} \tag{41}$$

Considering the situation, time derivative of Lyapunov function is negative and control system is asymptotically stable [13].

3. Results and Analysis

In order to make sure about the proposed controller, a simulation of the power system and the controller is performed. Then using the simulation, controller capability is studied. It is noteworthy that the proposed controller is combined with SMC and fuzzy controller.

3.1. Simulation

In order to simulate a power system, Matlab 2013 is used. A system of an asynchronous induction turbine is considered for simulation. The system parameters are shown in Table 1.

Table 1. Induction Turbine Parameters

Parameter	Value
Rotor type	Wound
Reference frame	rotor
Nominal power	1.5 MW
Voltage(line-line)	400V
Frequency	50Hz
Stator resistance(pu)	0.023
Stator inductance(pu)	0.18
Rotor resistance(pu)	0.016
Rotor inductance(pu)	0.16
Mutual inductance(pu)	2.9

As it is shown, the power system is a 1.5 MW wind turbine with DFIG witch is connected to a 400 volts' power line The DFIG is an AC-DC-AC converter with 10 milifarad capacitor. Besides, a 50 VAR capacitor bank is used to eliminate generator's induction effect on the network. The Output Voltage of the wind turbine is 575 volts. The parameters of AC-DC-AC converter is shown in Table 2.

Table 2. Converter Parameters

Parameter	Value
Number of bridge arms	3
Snubber resistance Rs (Ohms)	1K
Snubber capacitance Cs (F)	Inf
Power Electronic device	IGBT/Diode
Ron (Ohms)	1e-4

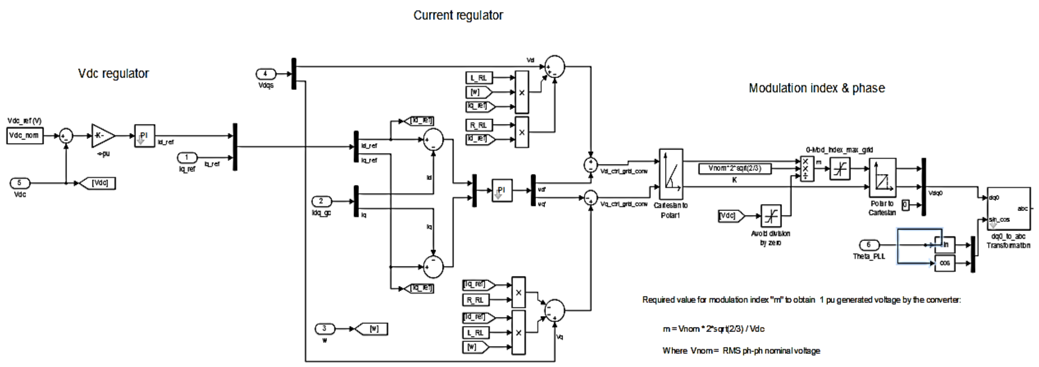

Figure 3. Fuzzy Control of the IGBT Pulses Toward Network

The proposed controller uses line voltage, 3 phase current of the stator, 3 phase current of the line, rotor current, DC voltage, rotor angle, turbine angular velocity as input. The controller is consisted of fuzzy and sliding mode controller. The output of the controller is AC-DC-AC converter PWM signal, pitch angle of the wind turbine blade and active and reactive power of the system.

The controller is divided into 4 parts.

a. Measuring and fitering
b. Control of converter toward network
c. Control of converter toward rotor
d. Control of pitch angle and velocity

For each of these parts, different control laws can be utilized.

3.2. Results

At first, the results of fuzzy controller are discussed. Four different scenarios described as follows, are studied.

a. Control of converter pulses toward rotor
b. Control of converter pulses toward network

c. Control of velocity and angle
d. Control of all above items simultaneously

Fuzzy controller implemented for controlling IGBT pulses toward network is illustrated in Figure 3. Other controlling blocks are considered as default mode of Matlab software. Inputs are PLL angle, velocity, measured DC voltage, d-q unit voltage and current.

Measured curves for the scenarios are depicted in Figure 4.

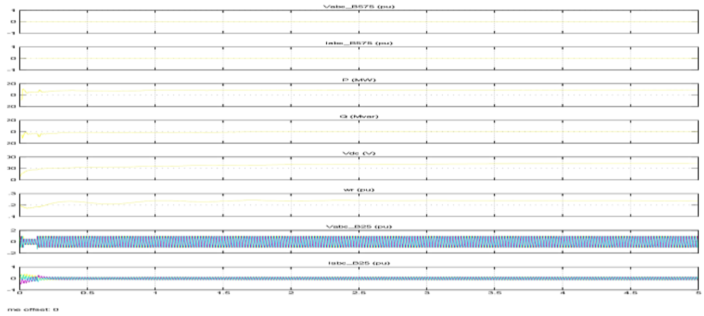

Figure 4. Fuzzy Control Implementation on Converter Pulses Toward Network

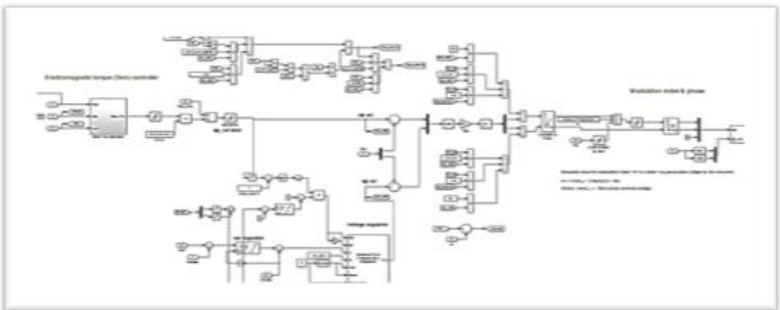

Figure 5. Fuzzy Control Implementation to the Rotor Pulses Control

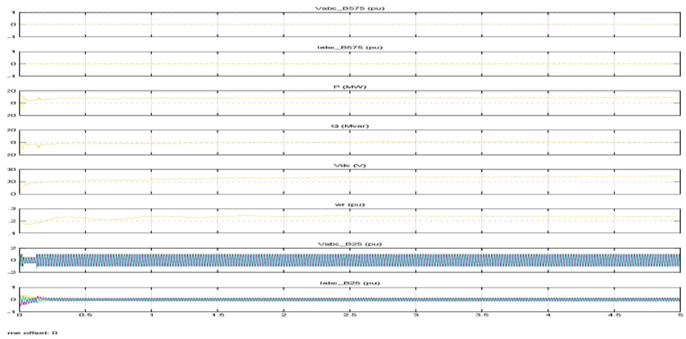

Figure 6. System Output in the Presence of Fuzzy Control Implemented to the Control of Rotor Pulses

As seen in Figure 4, system transient response reaches to persistence point and stabilizes in 0.2 seconds and system output is not fluctuating. Rotor speed had fluctuated before reaching a constant value after 1.5 seconds. Produced power (active and reactive) reaches a stable state after 0.2 seconds.

Fuzzy control implemented against IGBT pulses toward network is illustrated in Figure 5. Inputs of this controlling unit are dq voltage related to stator, dq current of the stator and rotor, velocity, angle of rotor, rotor velocity and stator voltage. Output of this scenario is presented in Figure 6.

As seen in Figure 6, time needed to reach stable mode in output is 0.3 seconds and it takes longer for the system's capable output to reach to the permanent mode compared to the structure of controller toward rotor. Generally, this time is suitable for the wind's production system. Figure 7 illustrates implementation of fuzzy control to the angle and velocity control structure. Velocity and angle control unit of blades are presented in Figure 7. Inputs of this structure are measured velocity and power of the output. Output of this structure is presented in Figure 8. As seen in Figure 8, time needed to reach the stable mode is 0.25 seconds which is shorter than the previous scenario. Moreover, system's voltage stability is quicker than 0.1 sec.

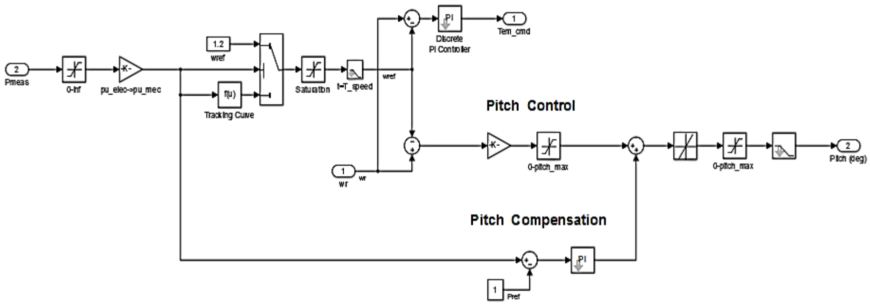

Figure 7. Fuzzy Control Implementation to the Structure of the Velocity Control Unit and Control of the Turbine's Blade Angle

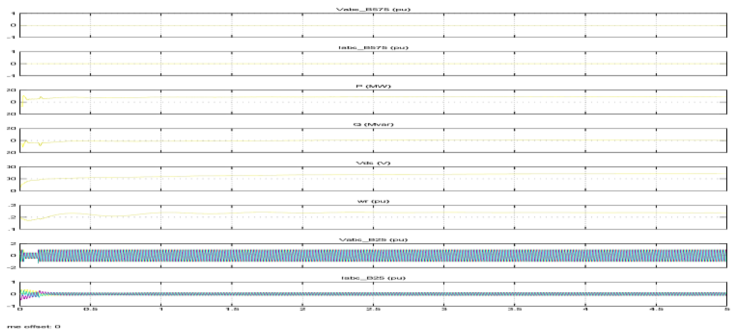

Figure 8. System Output in the Presence of Fuzzy Control Implemented to Velocity and Blade Angle Control Unit

Fuzzy control implementation on all control units are presented here. The results of the implementation are accurate because vector control in each unit doesn't yield a reliable result because of the previous default unit rejection shortage but fuzzy control implementation to all of these structures shows system ability in stabilizing by fuzzy and power control. Figure 9 shows system output in the presence of fuzzy control implemented to the all structure of the control.

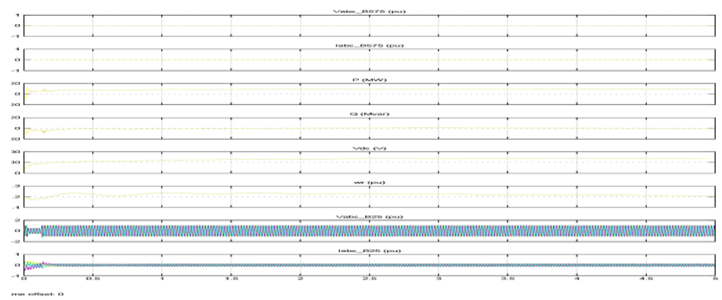

Figure 9. System Output for Fuzzy Control Implementation to the All Control Structure

As seen in Figure 9, time for reaching stable mode doesn't change compared to the first scenario. Therefore, this system in the first scenario of the fuzzy control can have a better performance. Moreover, voltage becomes stability is 0.2 seconds which is acceptable and suitable compared to previous modes. Sliding mode control structure implementation toward the system is presented as following.

Sliding mode controller is applied to the system and changes in the results will be available for these two systems. Figure 10 shows desired system output in the presence of sliding mode control against structure of the network pulses control unit. As seen in this figure, time needed to reach stable mode is 0.15 seconds which has improved about 0.05 seconds compared to fuzzy control. On the other hand, power fluctuations have decreased regarding outputs in active and reactive power. Moreover, DC voltage output experienced minor changes and fluctuations. These fluctuations are about 1 volt. System was able to reach stability in the period of 1.4 seconds and the changes were minor.

Figure 11 shows sliding mode controller effects on converter pulses control toward rotor.

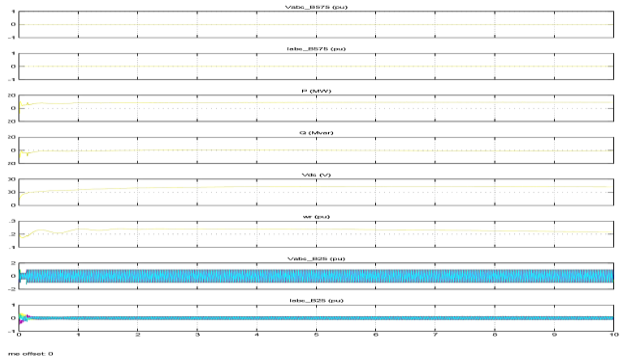

Figure 10. Expected System Output for Sliding Mode Control Implementation to the Network Control Pulses Unit

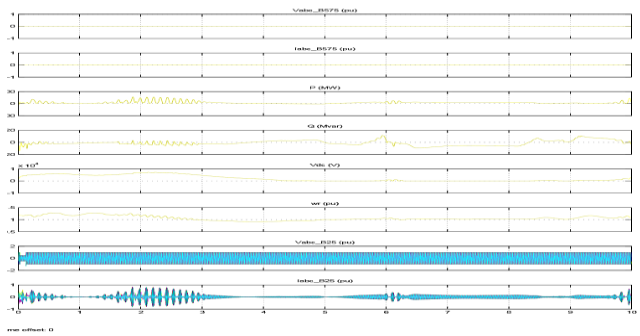

Figure 11. Sliding Mode Control Implementation to the System of Figure 1 in the Rotor Pulses Control

As seen in Figure 11, system experiences instability and the output is not valid. Therefore, it can be concluded that sliding mode control experienced some problems on the rotor's side converter control and the final results were not valid and this causes system to be unstable. Therefore, fuzzy control shows better response.

Figure 12 shows sliding mod control implementation on the velocity and blade's angle control unit. As seen in the figure sliding mode structure could take system to stable mode in a matter of 0.16 seconds. It can reduce power fluctuating in active and reactive modes. On the other hand, system has shown much ability in reducing ripples on the voltage. Figure 13 shows sliding mode control implementation in all the controller structures. As seen, sliding mode control structure effectively stabilizes the system which is presented in Figure 4, compared to fuzzy control by about %5 (time criteria to reach stable mode). Sliding mode controller reduced the fluctuation of other parameters including DC voltage, active and reactive power and rotor velocity. All these are easily seen from the comparisons of the figures.

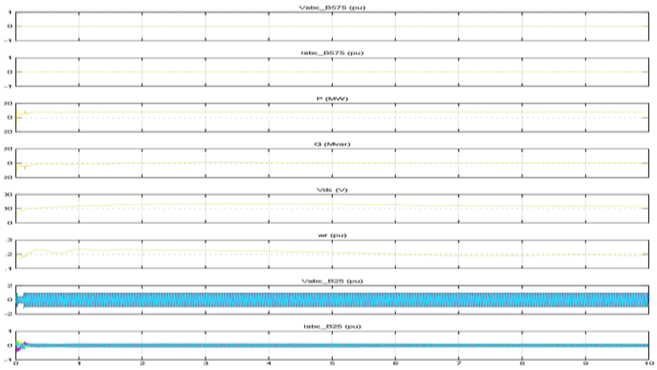

Figure 12. Sliding Mode Control Implementation on the Velocity and Blade's Angle Control

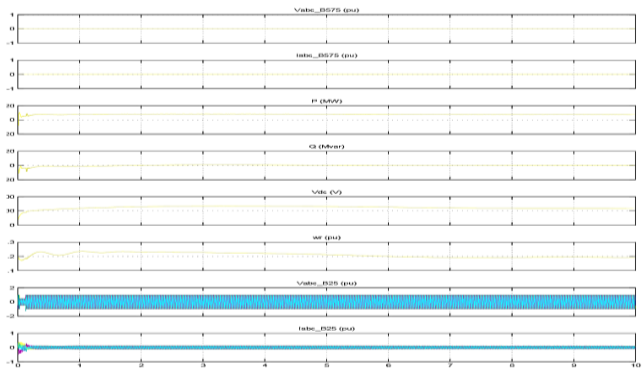

Figure 13. Applying Sliding Mode Control to the System

4. Conclusion

The power system, studied in this paper, is a turbine and a single governer of a synchronous machine which is connected to an infinite bus of a power line. The problem with the power system is the controller wich is used to stabilize the turbine. CPSS, FPSS and SMC controllers are examples of controllers which are used to stabilize the power system. Robustness of the controller in the presense of uncertainty without any chattering is very important. CPSS, FPSS and SMC are not robust enough in the presence of the uncertainties. In this Paper, fuuzy controller is combined with sliding mode controller to form a robust controller. The proposed controlled is very robudst in the presense of big uncertsinty. In order to be sure about the robustness of the controller a simuation is used. The simulation shows that the controller is more powerfull in damping fluctstions than other common controllers.

References

[1] SC Singhal. Solid oxide fuel cells for stationary, mobile and military applications. Solid State Ionics. 2012; 152: 405-410.

[2] R Anahara, S Yokokawa, M.Sakurai. *Present status and future prospects for fuel cell power systems*. Proc., IEEE. 1993; 81: 399-407

[3] YH Li, SS Choi, S Rajakaruna. An analysis of the control and operation of a solid oxide fuel-cell power plant in an isolated system. *IEEE Trans., Energy Conversion*. 2005; 20: 381-387.

[4] XJ Liu, CW Chan. Control of a solid oxide fuel cell power plant in a grid-connected system. *IEEE Trans., Energy Conversion*. 2005; 99: 1-1.

[5] M Gopal. Digital control and state variable methods. TATA McGraw Hill edition.

[6] Jianxin Tang. PID controller using the TMS320C31 DSK with on-line parameter adjustment for real time dc motor speed and position control. *IEEE-ISIE*. 2001: 786-791.
[7] Tarun Gupta, RR Boudreaux, RM Nelms, John Y Hung. Implementation of a fuzzy controller for DC-DC converters using an inexpensive 8-b Microcontroller. *IEEE Transactions on Industrial Electronics.* 1997; 44(5).
[8] Pena R, Clare JC, Asher GM. *Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation*. IEEE Proc., Electr. Power Appl. 1996; 143(3).
[9] Jenn-Kun Kuo, Chi-Fa Wang. An integrated simulation model for PEM fuel cell power systems with a buck DC-DC converter. *International Journal of Hydrogen Energy*. 2011; 1184-1185.
[10] Ben Saad, K Sahbani, M Benrejeb. Design Procedure and Implementation of a Robust Fuzzy Sliding Mode Controller for Buck Converters. *International Review of Automatic Control*. 2008; 1: 303-310.
[11] So WC, Tse CK, Lee YS. Development of a fuzzy logic controller for DC/DC converters: design, computer simulation and experimental evaluation. *IEEE Trans., Power Electronics*. 1999; 32, 11:24.
[12] S Srimongkol, S Rattanamongkonkul, A Pakapongpun. Mathematical Modeling of Fuel Cell Cathode with High Temperature. *International Journal of Mathematical Models and Methods in Applied Science*. 2012; 6(6).