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Fuzzy Bassed Gain Scheduled PI Controller for an Isolated Wind-Diesel Hybrid Power System

R.Goutham Govind Raju, S. Mohamed Ali
Department of Electrical and Electronics Engineering, CK College of Engg & Tech,
Caddalore, Tamilnadu India.
e-mail: goutham_178@rediffmail.com, sma1005@gmail.com

Abstract

Electrical power is the vital input for the economic development of any developing country. At their zenith, many excellent methods for the generation of power have been developed. The cost of supplying electrical power through grid to rural areas is becoming excessively high due to large investments in transmission and distribution lines, centralized power generating stations and line losses. For these reasons, the stand alone decentralized power generating stations with non-conventional energy sources like wind, biomass, solar energy, micro and mini hydel sources are being considered for electrifying remote rural areas. Hence in this paper an isolated wind-diesel hybrid power system with superconducting magnetic energy storage unit is considered. The hybrid power system is normally equipped with a control system, which functions to reduce the system frequency oscillations and makes the wind turbine generator power output follow the performance curve when the system is subjected to wind/load disturbances. Usually PI controllers are employed in these systems. Unfortunately, since the operating point continuously changes depending on the demand of consumers, this constant gain PI controller are unsuitable to other operating points. Therefore, this paper describes the application of the fuzzy gain scheduling on the PI controller for an isolated wind-diesel hybrid power system with superconducting magnetic energy storage unit.

Keywords: *Wind-diesel power system, fuzzy gain scheduled PI controller, SMES unit.*

1. Introduction

Electrical energy demand is increasing constantly and this demand has to be met by a planned electrical power generation programme. Although electrical energy is environmentally the most benign form of energy, its production is routed through burning of conventional fossil fuel or nuclear energy or hydro resources. All of these, in addition to other disadvantages, give rise to environmental issues of varied nature. To minimize the environmental degradations, one of the solutions is to utilize wind energy in favorable remote sites, away from the centralized energy supply systems [1].

However, the wind power generation has its own characteristics that are different from the existing generation systems such as the wind dependence caused inconsistency in the generation of electric power. A wind power station may be fully supplying an ‘autonomous’ load at one moment and may be in considerable power deficit only seconds later. Thus wind power generation introduces uncertainty in operating a power system and it is continuously variable and difficult to predict. Since wind power varies randomly there must be a stand-by power source to meet load demand. Hence there is a need for some magic formula such as wind combined with diesel [2].

The operation of diesel generator set for extended periods at low power level (less than 50%) could result in engine damage together with a reduction in engine life time. So, a simple diesel generator back-up may not be sufficient and there is a need for reliable energy storage medium. In case of strong wind or less load demand the excess energy can be stored in energy storage unit which can share the sudden changes in power requirements.

Energy storage is an attractive option to augment demand side management implementation. By using energy storage systems, a low cost source of electricity can be efficiently provided to meet the peak demand. An energy storage device can be charged during off-peak periods and the stored energy is used during peak periods [3].

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SMES is suggested as storage unit for improving the dynamic performance of wind–diesel hybrid power systems. An SMES unit is a device that stores energy in the magnetic field generated by the dc current flowing through a superconducting coil [4]. During high wind speed and less load demand the excess energy will be stored in the magnets with superconductive windings of SMES unit. Fast acting energy storage such as SMES can effectively damp out electromechanical oscillations in a power system, because it provides storage capacity in addition to kinetic energy of the generator rotor, which can share the sudden changes in power requirement.

The isolated wind-diesel hybrid power system with superconducting magnetic energy storage unit is normally equipped with a control system, which functions to reduce the system frequency oscillations and makes the wind turbine generator power output follow the performance curve when the system is subjected to wind / load disturbances. Usually PI controllers are employed in these systems. These PI controllers result in relatively large overshoots in transient frequency deviations. Further, the settling time of the system frequency deviation is also relatively high [5-8]. Gain scheduling is a technique commonly used in designing controller for non-linear systems. Its main advantage is that controller parameters can be changed very quickly in response to changes in the system dynamics because no parameter estimation is required. Besides being an effective method to compensate for non-linear and other predictable variations in the system dynamics, it is also simpler to implement than automatic tuning or adaptation. However, conventional gain scheming also has its drawbacks. One drawback is that the system parameter change may be rather abrupt across the regional boundaries, which may result in unsatisfactory or even unstable performance across the transition regions [9, 10]. Hence this paper describes the application of fuzzy gain scheduling on the PI controller for an isolated wind-diesel hybrid power system with superconducting magnetic energy storage unit.

2. Mathematical Modeling

The basic configuration of a wind and diesel turbine generators with SMES unit is shown in Figure 1.

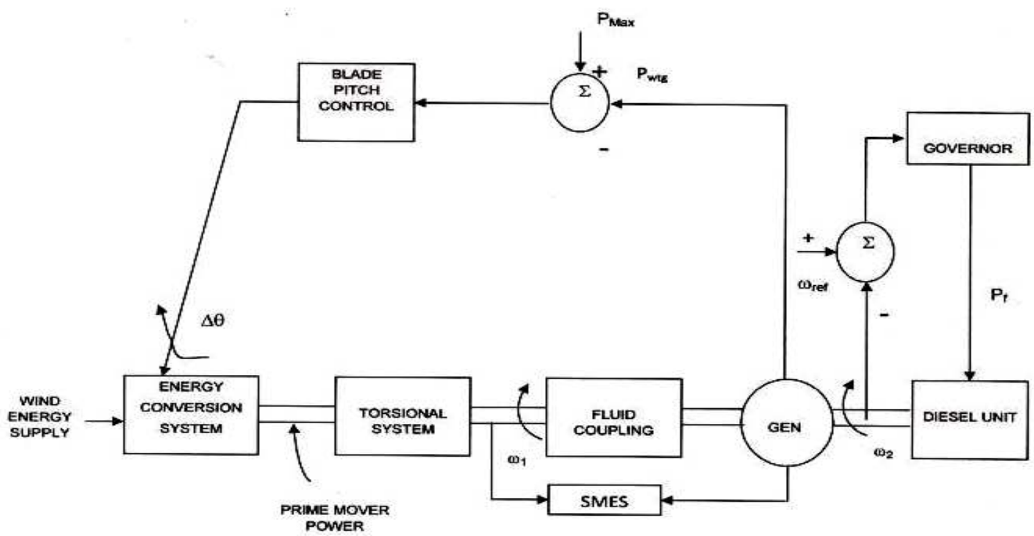

Figure.1 Basic configuration of wind and diesel turbine generators with SMES units

The model considered here consists of the following sub-systems [4]:

1. Wind dynamic model,
2. Diesel dynamic model,
3. Superconducting magnetic energy storage unit,
4. Blade pitch control of wind turbine,
5. Generator dynamics model.

The wind model is one feature that is unique to the wind turbine generator and is not required for the diesel generator system in the stability programme. The basic conditions for start up and synchronization are that the wind speed is to be within an acceptable range and there must be a phase match between the generator and system voltages.

The diesel dynamics is associated with diesel power and the nature of the dynamic behaviour in this model is dominated by the diesel engine speed governor controller. A total power set point is selected in which it can manually adjusted from zero to maximum value. The purpose of the adjustable power set point is to allow system utility personnel to lower the power setting to a value below the maximum setting of the wind generator to prevent engine power from dropping to less than 50% of the rated power. Operation of a diesel engine for extended periods at low power levels could result in engine damage.

During high wind speed and less load demand the excess energy will be stored in the magnets with superconductive windings of SMES unit. Such superconducting magnetic energy storage systems would consist of a superconducting inductor, a helium refrigerator and dewar system to keep the temperature well below the critical temperature for the superconductor, and an ac/dc converter. Charging and discharging is achieved by varying the DC voltage, applied to the inductor, through a wide range of positive and negative values. This can be achieved by controlling the delay angle of commutation. Though the SMES technology is new and currently quiet expensive, it is a fast developing one and holds high promise. The intensive search for high temperature superconducting materials gives further impetus for studying the applications of this technology.

Generator dynamics model consists of a synchronous generator driven by a diesel engine through a flywheel and connected in parallel with an induction generator driven by a wind turbine. The diesel generator will act as a dummy grid for the wind generator which is connected in parallel. Variations of electrical power due to change in wind speed should be as small as possible; this is obtained by using the induction generator as a wind turbine drive train. Unlike synchronous generators, induction generator is high compliance couplings between the machine and the electrical system. This is true for induction generators with slip of at least 1-2% at rated power. The controlled variables are turbine speed and shaft torque. Control acts on the turbine blade pitch angle (pitch control). Since the torque speed characteristic of the induction generator is nearly linear in the operating region, torque changes are reflected as speed changes. Therefore, it is possible to provide a single speed controller to control speed as well as torque [6, 7].

2.1. Description Of Superconducting Magnetic

The basic configuration of SMES unit in the wind-diesel hybrid power systems is shown in Figure 2. When wind power rises above the power set point, the superconducting coil can be charged to a set value, (less than the full charge) from the wind turbine generator during normal operation of the system.

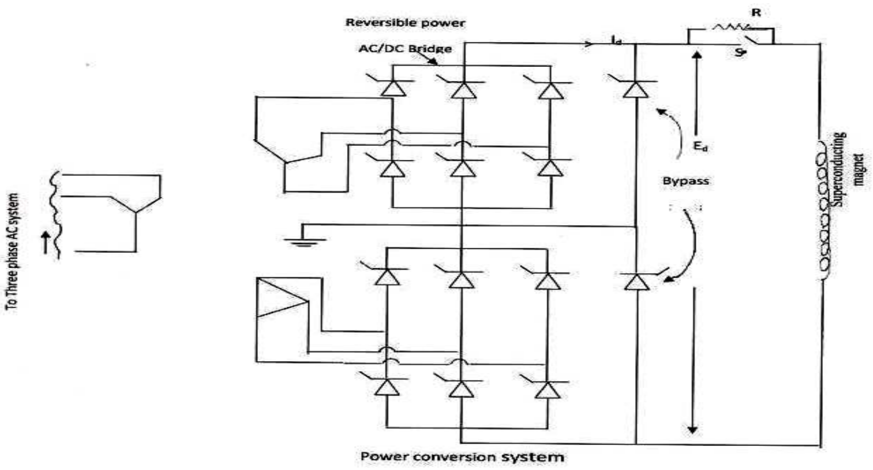

Figure. 2 Configuration of SMES unit in hybrid power systems

The DC magnetic coil is connected to the wind turbine generator through a power conversion system which includes an inverter /converter. Once the superconducting coil gets charged, it will conduct current, which supports an electromagnetic field, with virtually no losses. A helium refrigerator and dewar system is used to keep the temperature well below the critical temperature for the superconductor.

When there is a sudden rise in the demand of load, the stored energy is immediately released through the hybrid power system. As the governor and pitch control mechanisms start working to set the power system to the new equilibrium condition, the coil charges back to its initial value of current. Similar is the action during sudden release of the loads. The coil immediately gets charged towards its full value, thus absorbing some portion of the excess energy in the system, and as the system returns to its steady state, the excess energy absorbed is released and the coil current attains its normal value. For protection of the equipment a path for the inductor current must always be provided in case of faults such as disconnection of the converter transformer. This is done by connecting two bypass SCRs. In case of internal trouble (inside the dewar), conceivably it might be desirable to dump energy externally. The resistor R is intended to serve such purpose [6].

2.2. Mathematical Representation and Control of SMES

Control of the delay angle of commutation α, provides the means for varying continuously the bridge voltage E_d throughout a wide range of plus and minus values. The operation of SMES unit, that is charging, discharging, the steady state mode and the power modulation during dynamic oscillatory period is controlled by the application of the proper positive or negative voltage to the inductor. If losses are assumed negligible, the DC voltage is given by [6]

$$E_d = 2V_{d0}\, Cos\,\alpha - 2I_d R_c \quad (1)$$

where

E_d = DC voltage applied to the inductor, kV

V_{do}= Maximum open circuit bridge voltage of each 6-pulse converter at $\alpha = 0^o$, k

α = Firing angle, degrees

I_d = Current through the inductor, kA

R_c = Equivalent commutating resistance, ohm

The inductor is initially charged to its rated current, $I_{do,}$ by applying a small positive voltage. Once the current attains the rated value, it is held constant by reducing voltage ideally to zero. Since the coil is superconducting a very small voltage may be required to overcome the commutating resistance. The energy stored at any instant is

$$W_L = \frac{LI_d^{\,2}}{2} \text{ in } MJ \quad (2)$$

where L = inductance of SMES system in Henries.

Once the rated current in the inductor is reached, the unit is ready to be coupled with the hybrid power system. The wind frequency deviation $\Delta\omega_1$ of the power system is sensed and used to control the SMES voltage $E_{d.}$ During sudden loading in the system, the frequency will fall and SMES gets discharged. The control voltage E_d is to be negative since current through the inductor and the thyristors cannot change its direction. The incremental change in the voltage applied to the inductor is expressed as

$$\Delta E_d = \frac{K_o}{1 + sT_{dc}} \Delta\omega_1 \quad (3)$$

where

ΔE_d = The incremental change in converter voltage, kV

T_{dc}= Converter time delay, sec

K_o= The gain of the control loop, kV/Hz

s= The laplace operator, d/dt.

The incremental change in the current applied to the inductor is,

$$\Delta I_d = \frac{1}{sL}\Delta E_d \tag{4}$$

Power into the inductor at any time, $P_d = E_d \times I_d$ and initial power flow into the coil is $P_{d0}=E_{d0} \times I_{d0}$. Where E_{d0} , I_{d0} are the magnitudes of voltage and current prior to the load disturbance. In the response to the load disturbance the power flow into the coil can be expressed as,

$$P_d = (E_{d0} + \Delta E_d) \times (I_{d0} + \Delta I_d) \tag{5}$$

Thus the incremental change in power flow per unit is given by,

$$\Delta P_d = (I_{d0}\, \Delta E_d + \Delta E_d\, \Delta I_d) / P_R \quad \text{p.u} \tag{6}$$

The SMES unit has a natural tendency of current restoration which is a very slow process and artificial enhancement of rate of restoration is required. Use of inductor current deviation feedback in the SMES control loop is suggested here. The inductor current deviation can be sensed and used as a negative feedback signal in the SMES control loop to achieve quick restoration of current. Then, with frequency deviation as control signal,

$$\Delta E_d = \frac{1}{1+sT_{dc}}\left[K_o \Delta\omega_1 - K_{Id}\Delta I_d\right] \tag{7}$$

where K_{Id} is the gain corresponding to the ΔI_d feedback, kV/kA. The block diagram representation of such a control scheme is shown is Figure 3.

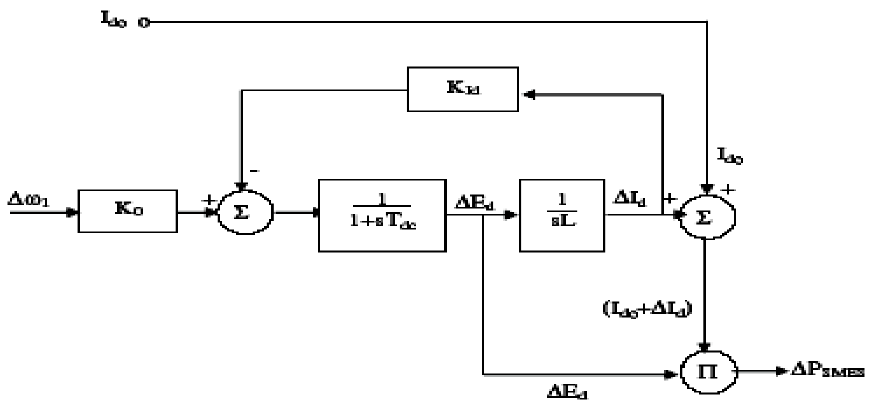

Figure. 3 Block diagram representation of the SMES unit control with inductor current deviation feedback

2.3. Transfer Function Model

Since the system is exposed to a small change in load during its normal operation, the linear model will be sufficient for its dynamic representation. Therefore, a small perturbation transfer function model block diagram of isolated wind-diesel hybrid power system with SMES unit is shown in Figure4 [8].

A linear continuous-time dynamic model can be described in the state space form as

$$X = A\dot{x} + bu + \gamma d \tag{8}$$

$$Y = Cx \tag{9}$$

where,

$X = [\Delta\omega_1\ \Delta P_M\ \Delta P_{M1}\ \Delta P_{M2}'\ \Delta\omega_2\ \Delta P_{f1}\ \Delta P_f\ \Delta E_d\ \Delta I_d]^T$ is the 9[th] order state vector.

$d = \Delta P_{load} + \Delta E_d\ \Delta I_d$ is the scalar disturbance input

u = u is the scalar control input and
Y = ΔP_{wtg} is the scalar output
A = System state matrix.
b = Input distribution vector.
γ = Disturbance distribution vector.
C = Output distribution vector

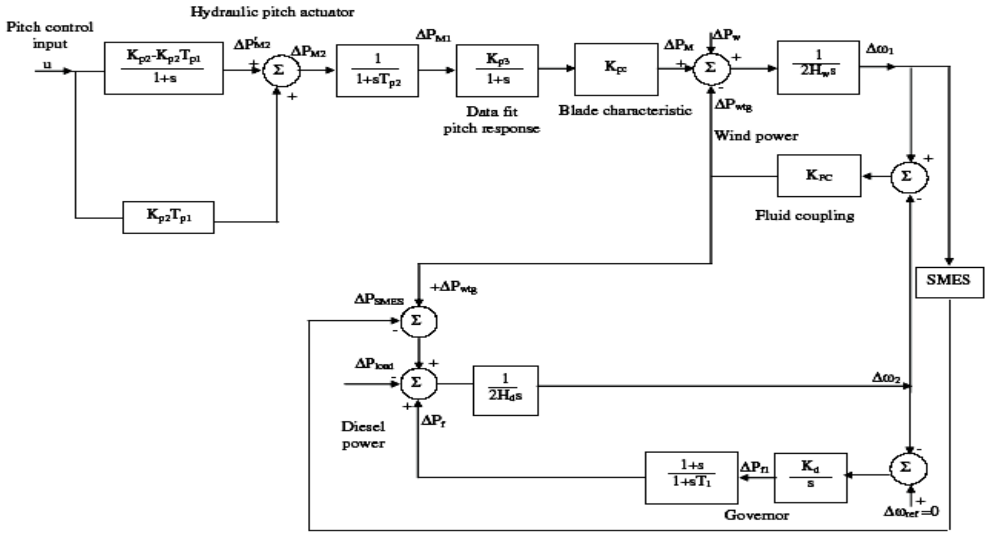

Figure.4. Transfer function model block diagram of isolated wind–diesel hybrid power systems with SMES unit.

3. Output Feedback Control Scheme

It is known that by incorporating an integral controller the steady state requirements can be achieved. In order to introduce an integral function to the controller the system equation (8) is augmented with a new state variable defined as the integral of ΔP_{wtg} ($\int \Delta P_{wtg} dt$). The augmented system of 8th order can be described as

$$\dot{\bar{x}} = \bar{A}\mathrm{x} + \bar{b}\,u + \bar{\gamma} d \tag{10}$$

where $\bar{x} = \begin{bmatrix} \int \Delta P_{wtg}\, dt \\ \bar{x} \end{bmatrix}$

$$\bar{\mathrm{A}} = \begin{bmatrix} 0 & C \\ 0 & A \end{bmatrix}, \quad \bar{b} = \begin{bmatrix} 0 \\ b \end{bmatrix} \quad and \quad \bar{\gamma} = \begin{bmatrix} 0 \\ \gamma \end{bmatrix}$$

As the newly added state variable ($\int \Delta P_{wtg} dt$) will also be available for feedback, the new measurable output $\bar{\mathrm{y}}$ can be written as

$$\bar{\mathrm{y}} = \bar{\mathrm{C}}\bar{\mathrm{x}} \tag{11}$$

where $\bar{\mathrm{y}} = [\int \Delta P_{wtg} dt,\ \Delta P_{wtg}]^T$ and

$$\bar{C} = \begin{bmatrix} 1 & 0 \\ 0 & C \end{bmatrix}$$

For the design of decentralized controller, the augmented system should be controllable and should not have unstable fixed modes. It can be easily shown that the augmented system will be controllable if and only if the given system is controllable and the matrix,

$$\begin{bmatrix} 0 & C \\ b & A \end{bmatrix} \text{ is of the rank } (1 + n)$$

The problem now is to design the output feedback control law,

$$u = k^T \bar{y} \tag{12}$$

to meet the desired output response of the system.The control law equation (12) can be written interms of ΔP_{wtg} as

$$u = -k_I \int \Delta P_{wtg} dt - k_P \, \Delta P_{wtg} \tag{13}$$

where $k^T = [-k_I, - k_p]$ is a 2-dimensional conventional integral and proportional controller constant feedback gain vector. Since the operating point continuously changes depending on the demand of consumers, this constant feedback gain output feedback control law is unsuitable to other operating points.

4. Design of Fuzzy Gain Scheduled PI Controller

In this work, we use this technique to schedule the parameters of the PI controller according to error (ΔP_{wtg}) and change of ΔP_{wtg}. As depicted in Figure 5.

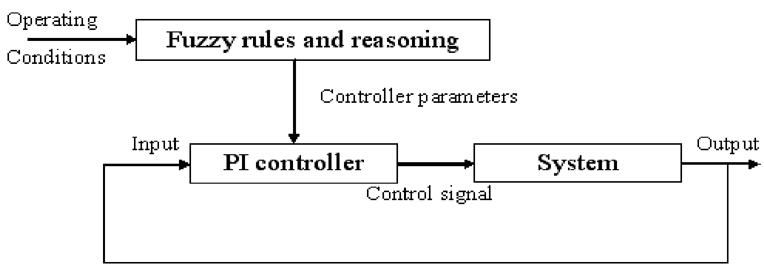

Figure.5. PI Control System with a Fuzzy Gain Scheduler

In this proposed scheme, the PI parameters, K_p and K_i are adjusted according to the current error and its first difference change of error. Both K_p and K_i are bounded within the prescribed ranges of $[K_{p,min}, K_{p,max}]$ and $[K_{i,min}, K_{i,max}]$ which are determined experimentally. K_p and K_i are each normalized into a range between zero and one by the following linear transformation,

$$K_p' = (K_p - K_{p,min}) / (K_{p,max} - K_{p,min}) \tag{14}$$

$$K_i' = (K_i - K_{i,min}) / (K_{i,max} - K_{i,min}) \tag{15}$$

Values of K_p' and K_i' are determined by a set of fuzzy rules of the form. If e(k) is A_i and Δe(k) is B_i, then

$$K_p' \text{ is } C_i \text{ and } K_i' \text{ is } D_i. \tag{16}$$

i = 1, 2, 3 . . . . . n.

where Ai, B_i, C_i and D_i are the fuzzy sets on the corresponding supporting sets.

The membership function (MF) sets for e(k) and Δe(k) are shown in Figure6, in which N, P, ZO, S, M, B, NB and NM represent respectively the linguistic level of negative, positive, approximately zero, small, medium, big, negative big and negative medium. The fuzzy sets C_i and D_i can either be Big or Small and are characterized by the membership functions shown in Figure7, where the grade of the membership functions μ and the variable x (= K_p' or K_i') have the following relations,

$$\mu_{Small}(x) = -(1/4)\ln x \text{ or } x_{Small}(\mu) = e^{-4\mu} \text{ (for Small)} \quad (17)$$

$$\mu_{Big}(x) = -(1/4)\ln(1-x) \text{ or } x_{Big}(\mu) = 1 - e^{-4\mu} \text{ (for Big)} \quad (18)$$

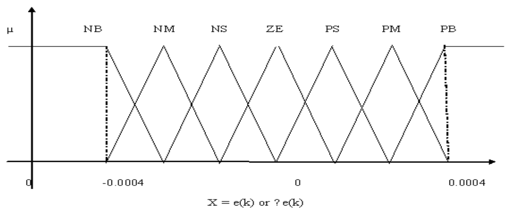

Figure.6. Membership functions for e(k) and Δe(k)

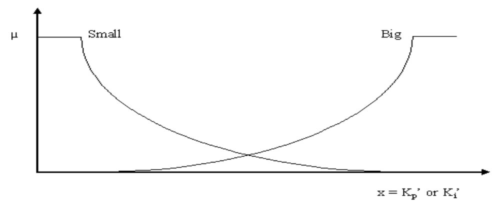

Figure.7. Membership functions for K_p' and K_i'

The output value of the i[th] rule in equation (4.3), μ_i is obtained by the product of the MF values of e(k) and Δe(k),

$$\mu_i = \mu_{Ai}[\, e(k)\,] \times \mu_{Bi}[\, \Delta e(k)\,] \quad (19)$$

where μ_{Ai} [e(k)] is the MF value of the fuzzy set A_i according to the value of e(k) and μ_{Bi} [Δe(k)] is the MF value of the fuzzy set B_i according to the value of Δe(k) [9,10]. Based on μ_i, the values of K_p' and K_i' for each rule are determined from their corresponding membership functions. The implication process of a fuzzy rule is shown in Figure 8. From the membership function in Figure 6, we can see that,

$$\sum_{i=1}^{n} \mu_i = 1 \quad (20)$$

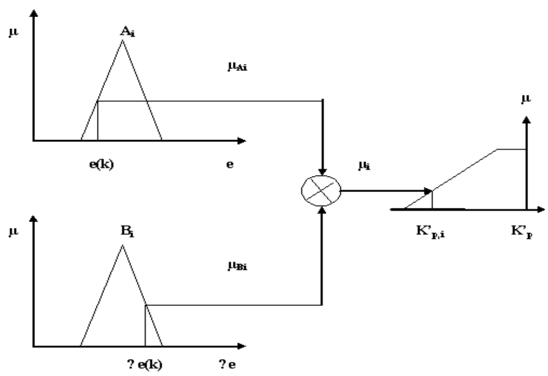

Figure .8. Implication process of fuzzy rule

Then, using the Center Of Area (COA) method, the Defuzzification yields the following [11, 12],

$$K_p' = \sum_{i=1}^{n} \mu_i K_{p,i}' \quad (21)$$

$$K_i' = \sum_{i=1}^{n} \mu_i K_{i,i}' \quad (22)$$

where $K_{p,i}$' is the value of K_p' corresponding to the grade μ_i for the i^{th} rule, and $K_{i,i}$' is obtained in the same way. After getting the Kp' and Ki', the PI controller parameters are calculated from the following equations,

$$K_p = (K_{p,max} - K_{p,min})\, K_p' + K_{p,min} \quad (23)$$
$$Ki = (K_{i,max} - K_{i,min})\, Ki' + K_{i,min} \quad (24)$$

5. Simulation Results

The fuzzy gain scheduling PI controller discussed above is implemented to an isolated wind-diesel hybrid power system with SMES unit. Simulations are carried out for a step load change of 1% disturbance and the resulting wind generator frequency deviation ($\Delta\omega_1$), diesel generator frequency deviation ($\Delta\omega_2$), wind generator power deviation (ΔP_{wtg}) and diesel generator power deviation (ΔP_f) are shown in Figure 9. The results are also compared with fixed gain PI controller. Figure9, it is found that the fuzzy gain scheduled PI controller has better transient and steady state performance over fixed gain PI controllers.

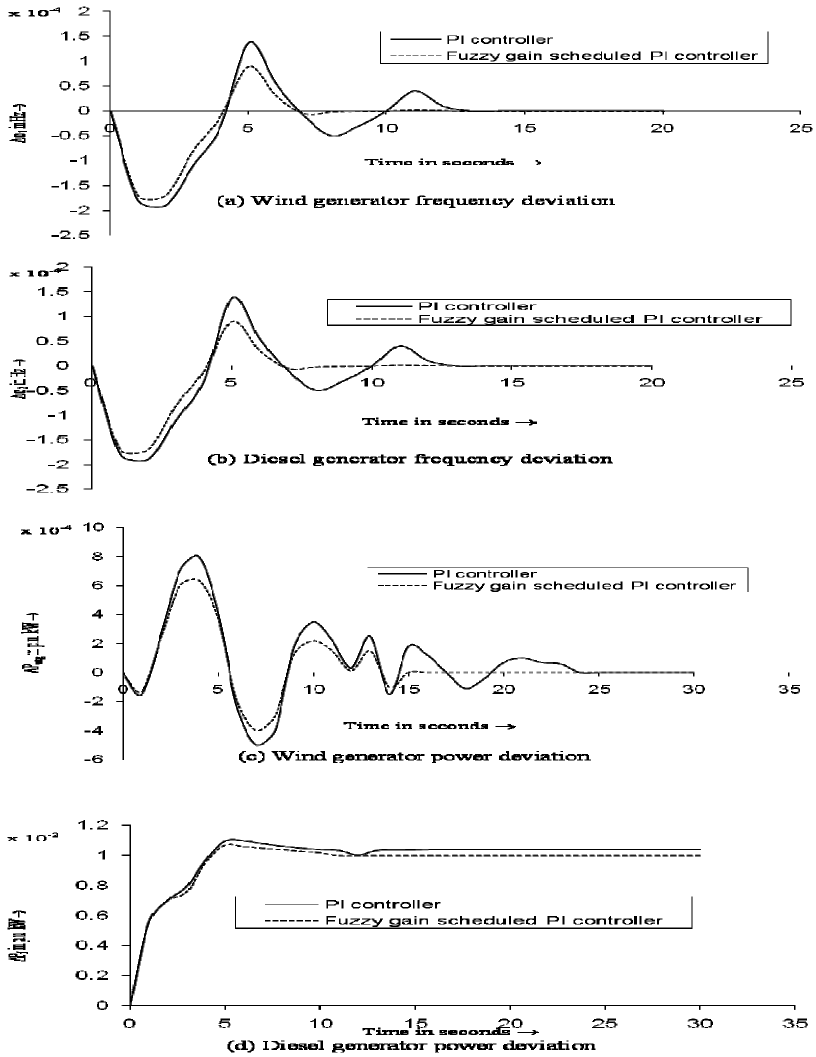

Figure. 9 Comparison of frequency and power deviation of wind-diesel hybrid power system with SMES unit with fixed gain PI controller & with fuzzy gain scheduled PI controller for a step load disturbance of 1%.

5.1 Robustness of Fuzzy Gain Scheduled PI Controllers

To assess the robustness of the proposed fuzzy gain scheduled PI controllers, the parameters T_{p2}, H_d, T_1, H_w and T_{dc} are varied by 20% from the nominal value one at a time, and simulations are carried out. The simulation results are shown in Figure 10. These results shows the robustness of the proposed controller for parameter variation.

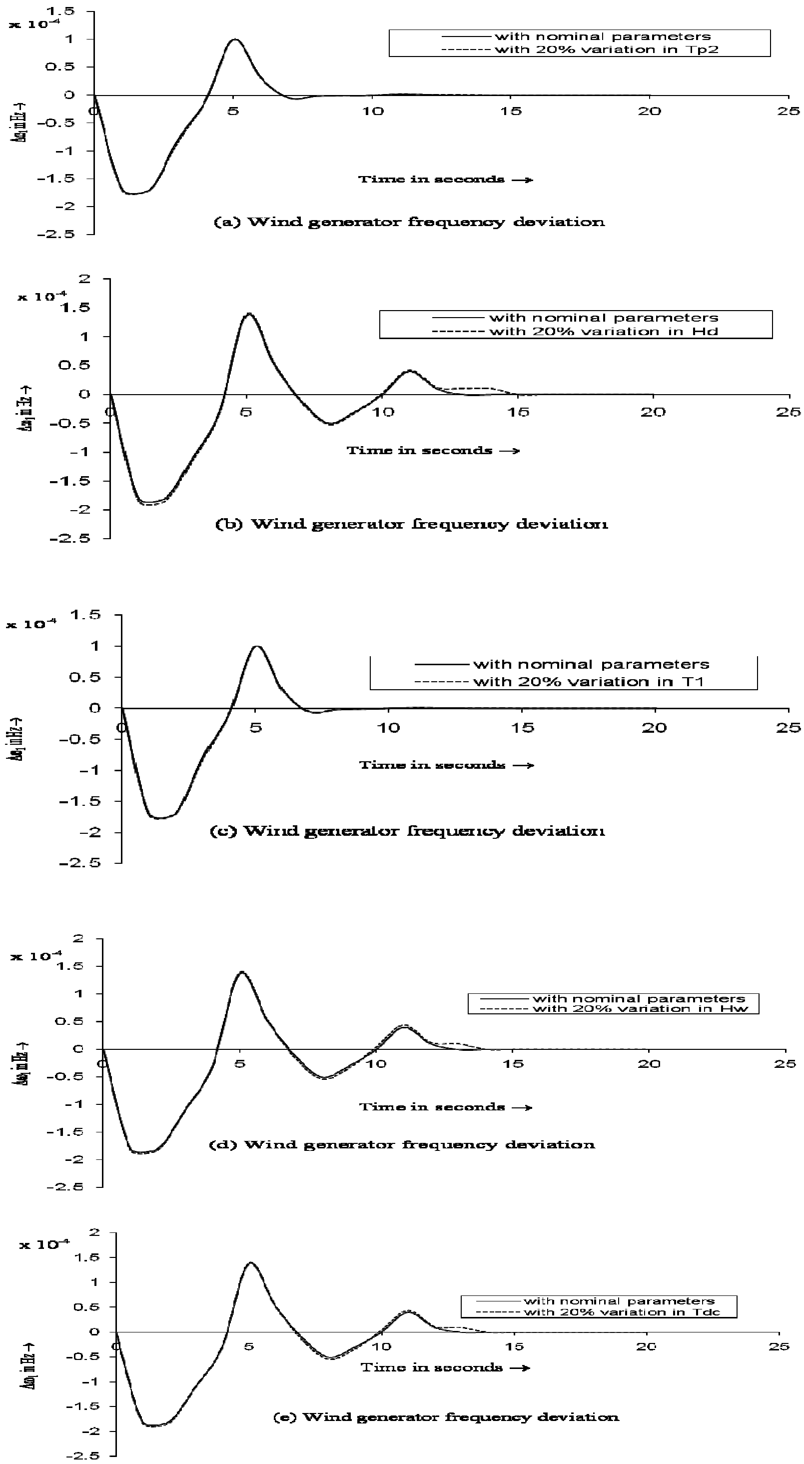

Figure.10 Comparison of wind generator frequency deviation for 1% step load change with 20% system parameter variation

6. Conclusion

In this work, a comprehensive mathematical model has been developed for an isolated wind and diesel turbine generators with SMES unit. The conventional PI controllers are designed by Eigen value sensitivity technique, implemented, simulations are carried out and the results are shown. Unfortunately, since the operating point continually changes depending on the demand of consumers, this constant gain PI controller are unsuitable to other operating points. Gain scheduling is a technique commonly used in designing controller for nonlinear systems. Its main advantage is that controller parameters can be changed very quickly in response to changes in the system dynamics because no parameter estimation is required. However, conventional gain scheduling also has its drawbacks. One drawback is that the system parameter change may be rather abrupt across the regional boundaries, which may result in unsatisfactory or even unstable performance across the transition regions. Hence in this paper the fuzzy gain scheduling of PI controller is carried out and the results are compared with fixed gain PI controllers. The result shows that the fuzzy gain scheduled PI controller has good transient and steady state performance over fixed gain PI controllers. Further, the robustness of the fuzzy gain scheduled PI controller is also tested by carrying out sensitivity analysis.

References

[1] Ahmet Duran Sahin, " Progress and recent trends in wind energy" , Progress in energy and combustion science, Vol. 30, 2004, PP. 501-543.
[2] D.Das, S.K. Aditya and D.P.Kothari, " Dynamics of diesel and wind turbine generators on an isolated power system" , Electrical power and energy systems, Vol. 21, 1999, PP. 183-189.
[3] Kyung Soo Kook, Keith J. Mckenzie, Yilu liu and Stanatcitty, " A study on applications of energy storage for the wind power operation in power system" , Proc. of IEEE, 2006, PP. 1-5.
[4] S.C. Tripathy,M. Kalantar, R. Balasubramanian," Dynamics and stability of wind and diesel turbine generators with superconducting magnetic energy storage unit on an isolated power system", IEEE Trans Energy Conversion, Vol. 6, Dec. 1991, PP. 579 - 585.
[5] G.W. Scott, V.F. Wilreker and R.k. Shaltins, " Wind turbine generator interaction with diesel generators on an isolated power system", IEEE transactions on Power apparatus and system, Vol. Pas -103, 5, May 1984, PP. 933-938.
[6] S.C. Tripathy and I.P. Mishra, "Dynamic performance of wind-diesel power system with CES", IEEE Energy conversion mgmt Vol.37, No. 12, 1996, pp 1787-1798.
[7] D. Das and D.P. Kothari," Instability and dynamics of wind turbine generator system on an isolated power system", Journal of Engineers (India), Vol. 76, Aug. 1995, PP. 69-78.
[8] M.Md. Thameem Ansari and S. Velusami, "Dual mode linguistic hedge fuzzy logic controller for an isolated wind–diesel hybrid power system with superconducting magnetic energy storage unit" Energy Conversion and Management, January 2010, PP. 169 - 181.
[10] Zhen-Yu Zhao, M. Tomizuka, S. Isaka ,"Fuzzy gain scheduling of PID controllers", IEEE transaction Systems, man and Cybernetics, Vol. 23, No. 5, 1993, PP. 1392 - 1398.
[11] C.S. Chang , Weihul fu, and Fushuan wen, "Load frequency control using genetic algorithm based fuzzy gain scheduling of PI controllers", Taylor & Francis, Electrical machines and power systems, 26, 1998, PP. 39 - 52.
[12] D. Drainkov, H. Hellendom and M.Penfranke, " An introduction to fuzzy control", Narusa publishing house, India.
[13] L. A. Zadeh, "Fuzzy algorithm", Information and control, Vol. 12, 1968, PP. 94-103.

Appendix

Wind- diesel system

P_R	=	350 kW
H_W	=	3.5 Seconds
H_d	=	8.5 seconds
K_{FC}	=	16.2 p.u.k W/Hz
K_{p3}	=	1.4
ΔP_{load}	=	0.01 p.u.kW
ΔP_W	=	0.0 p.u.kW
T_1	=	0.025 second
K_d	=	16.5 p.u.kW/Hz
T_{p2}	=	0.041 second

T_{p1} = 0.6 second
K_{pc} = 0.08

SMES Unit
I_{do} = 2.0 kA
L = 10.0H
K_{o} = 6000 kV/Hz
K_{Id} = 5.0 kV/kA