

Design of Dual Mode Linguistic Hedge Fuzzy Logic Controller for an Isolated Wind Power System

M. Md. Thameem Ansari* and S.Velusami**

Abstract:

In this paper, a dual mode linguistic hedge fuzzy logic controller (DMLHFLC) for an isolated wind power system is proposed. In this controller design, the dual mode control concept, superior characteristics inherent in the linguistic hedge, and the search ability of hybrid genetic algorithm – simulated annealing (GA-SA) algorithm are utilized. The system with the proposed controller is simulated and the frequency deviation resulting from a step load disturbance is presented. The comparison of the proportional plus integral (PI) controller, fuzzy logic controller (FLC) and proposed DMLHFLC shows that, with the application of the proposed controller, the system performance is improved significantly.

Key Words:

wind power system, dual mode linguistic hedge fuzzy logic controller, fuzzy logic controller

1. Introduction

In the recent years, the world wide interest and study are turned to renewable energy sources. Out of all renewable energy sources wind is placing a main role, because of its clean, safe and availability[1]. Wind is the fastest growing and most widely utilized of the emerging renewable energy technologies in electricity system at present. Wind is caused by heating of atmosphere by solar heating. Wind turbine converts the kinetic energy in the wind to rotary mechanical energy to electrical energy and drives the generator shaft. The electrical generator converts the mechanical energy to electrical energy.

Constant frequency system are essential for modern wind farms. As the output is either grid connected or delivered to consumers requiring constant frequency supply. By maintaining constant frequency, the wind turbine requires blade pitch control[2]. Pitch angle is the angle between the direction perpendicular to the surface of the blades.

A number of methods[3-6] are found in the literature for the suitable control. The conventional approach using PI controllers results in relatively large overshoots in transient frequency deviation. Further, the settling time of the system frequency deviation is also relatively long. FLC is a sophisticated technique[7] that is easy to design and implement. Nevertheless, the determination of membership functions and control rules is an essential part of the design. To achieve satisfactory membership functions and control rules, designer's experience is necessary. On the other hand, Zadeh proposed the fuzzy linguistic hedges to modify the membership function of the fuzzy sets [8]. By means of adjusting the membership functions dynamically through the linguistic hedge concept, fewer rules and simple shape membership functions can be employed to achieve a better performance when compared to conventional FLC.

Generally, it is difficult for a human expert to search for a number of proper rules for the fuzzy system. These problems can be solved by application of machine learning. Machine learning methods have, in recent years emerged from the use of learning algorithms modeled on natural and biological systems. One of these algorithms is genetic fuzzy systems[9]. Nowadays, many researchers have combined the control techniques to improve the efficiency of the control and optimization.

Therefore, this paper proposes by taking advantage of the superior characteristics in the linguistic hedges and the search ability of hybrid method a new design of dual mode linguistic hedge fuzzy logic controller (DMLHFLC) for an isolated wind power system. An important design concept of dual mode control is incorporated in the proposed fuzzy control because it improves the system performance and makes it flexible for application to actual systems. A hybrid genetic algorithm-simulated annealing (GA-SA) is used to search for optimal linguistic hedge combination in the linguistic hedge module. The computer simulation results of application of the proposed controller with wind power system prove that the proposed controller is effective and provides significant improvement in the system performance.

2. Development of mathematical model of an isolated wind power system

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 an isolated wind power system is shown in Fig. 1

A linear continuous – time dynamic model of the system can be described in the state space form.

* Dept. of Electrical Engineering, Annamalai University, India
E-Mail: ansari_aueee@yahoo.co.in

** Dept. of Electrical Engineering, Annamalai University, India, E-Mail: profvels@yahoo.co.in

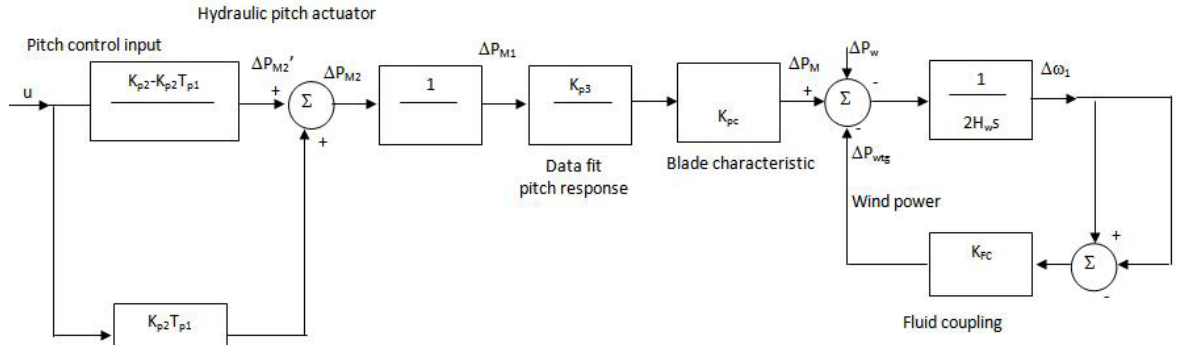


Fig. 1. Transfer function model block diagram of an isolated wind power system

$$\dot{\underline{x}} = \underline{A} \underline{x} + \underline{b} \underline{u} + \underline{\gamma} \underline{d} \quad (1)$$

$$\underline{y} = \underline{C} \underline{x} \quad (2)$$

where,

$\underline{x} = [\Delta P_{wtg}, \Delta P_M, \Delta P_{M1}, \Delta P_{M2}]^T$ is the 4th order state vector.

$\underline{d} = \Delta P_w$ is the scalar disturbance input

$\underline{u} = u$ is the scalar control input and

$\underline{y} = \Delta \omega_1$ is the scalar output

The constant matrices $\underline{A}, \underline{b}, \underline{\gamma}$ and \underline{C} are system state matrix, input distribution vector, disturbance distribution vector and output distribution vector respectively of appropriate dimensions

3. Design of proposed dual mode linguistic hedge fuzzy logic controller with output feedback

Since the principle of dual -mode control can improve the system performance [10], a new design of dual mode linguistic hedge fuzzy logic controller is proposed in this section. This DMLHFLC operates in mode A as long as the significant observed variables to the control actions the system output error is sufficiently large i.e. greater than the switching limit of the controller. Otherwise it operates in mode B. Mode A acts as proportional type linguistic hedge fuzzy logic controller and mode B as integral type linguistic hedge fuzzy logic controller. Thus, the control structure of the system is changed when switching in each mode of operation. Since DMLHFLC is designed based on the switching limit of the controller, the performance of the controller is improved significantly.

In a fuzzy logic based control system, the information is described linguistically. The linguistic hedge is an operator with an operation like a modifier used to modify the shape of membership functions [8]. The major difference between the proposed DMLHFLC and the conventional FLC is that a module called linguistic hedge module is inserted into the conventional one to adjust the shape of fuzzy membership functions dynamically

according to the feedback signal from the controlled plant based on the switching limit of the controller. The emerged interesting result is that the DMLHFLC maintains better performance even though the number of the inference rules is reduced to a number as small as possible. Only nine rules are used in each mode based on the switching limit of the controller. The block diagram of DMLHFLC shown in Fig. 2 consists of several modules similar to those in a conventional FLC except for the fuzzifier module and the linguistic hedge module attached to the fuzzifier module. Relying on the benefits described, the number of inference rules used in the DMLHFLC is nine for each mode. The fuzzy sets labeled negative big (NB), zero (ZE) and positive big (PB) are used in the proposed architecture since these are the most general and universal representations of membership functions used in fuzzy logic controls.

The triangular-shape membership function $\mu_{ZE}(x)$ of fuzzy set ZE can be expressed for each mode of operation as

$$\mu_{ZE}(x) = \begin{cases} 0, & -\infty < x \leq x_{NB} \\ -\frac{|x - x_{ZE}|}{x_{PB} - x_{ZE}} + 1, & x_{NB} \leq x \leq x_{PB} \\ 0, & x_{PB} \leq x < +\infty \end{cases} \quad (3)$$

Similarly the other membership function $\mu_{NB}(x)$ and $\mu_{PB}(x)$ can also be expressed.

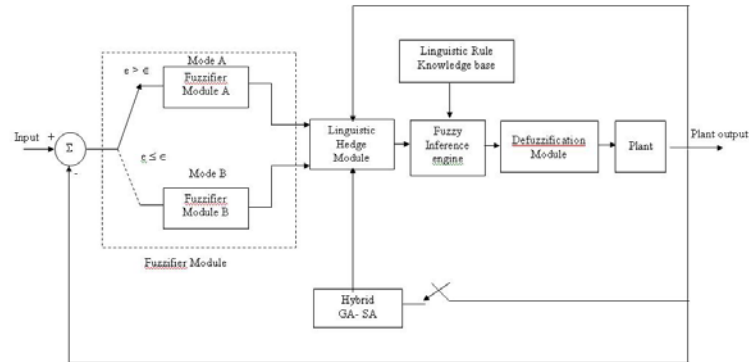


Fig. 2. Block diagram of dual mode linguistic hedge fuzzy logic controller

In order to apply the hedge operations to the proposed DMLHFLC, the domains of the input variables are partitioned into n intervals in each mode of operation. From the mathematical point of view, the membership functions $\mu_{NB}(x)$, $\mu_{ZE}(x)$, and $\mu_{PB}(x)$ seem to be assembled by n piecewise linear functions. These partitioned membership functions denoted as $\mu_{NB}'(x)$, $\mu_{ZE}'(x)$ and $\mu_{PB}'(x)$ can be expressed as

$$\begin{bmatrix} \mu_{NB}'(x) \\ \mu_{ZE}'(x) \\ \mu_{PB}'(x) \end{bmatrix} = \text{tr}(P(x)) \begin{bmatrix} \mu_{NB}(x) \\ \mu_{ZE}(x) \\ \mu_{PB}(x) \end{bmatrix} \quad (4)$$

$$P(x) = \begin{bmatrix} u(x-x_{NB}) - u(x-x_{NB}-\Delta) & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & u[x-x_{NB}-(n-1)\Delta] - u(x-x_{NB}-n\Delta) \end{bmatrix}_{n \times n} \quad (5)$$

Where $\text{tr}(\cdot)$ denotes the trace of a matrix and $P(x)$ is the partition matrix.

In which Δ denotes the step size of the input domain partition, and $u(x)$ is the unit step function of x defined as

$$u(x) = \begin{cases} 0 & -\infty < x < 0 \\ 1 & 0 \leq x < +\infty \end{cases} \quad (6)$$

The membership function in each interval $i(i=1, \dots, n)$ is now modified by the corresponding hedge operator h_i which is the i -th element of the hedge combination vector $h = [h_1 \dots h_n]$ defining the proper hedge operators of the n intervals of the whole input domain. For the sake of convenience of mathematical expression, the hedge combination matrix \mathbf{H} is defined as

$$\mathbf{H} = [h_1 v_1 \dots h_n v_n] = \begin{bmatrix} h_1 & 0 & \dots & 0 \\ 0 & h_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & h_n \end{bmatrix}_{n \times n} \quad (7)$$

where v_i is the i -th basis of n dimensional vector space, which is defined as

$$v_i = \begin{bmatrix} v_1 \\ \vdots \\ v_n \end{bmatrix}_{n \times 1} \quad (8)$$

and

$$v_j = \begin{cases} 1 & , j = i \\ 0 & , \text{otherwise} \end{cases} \quad (9)$$

That is, every entry of \mathbf{H} is 0 except the diagonal entries h_i ($i=1, \dots, n$) which give the hedge operators of the corresponding interval of membership function. Since the matrix \mathbf{H} is diagonal, the membership functions $\mu_{HoNB}(x)$,

$\mu_{HoZE}(x)$ and $\mu_{HoPB}(x)$ resulting from modification by corresponding hedge operators can be expressed as

$$\begin{bmatrix} \mu_{HoNB}(x) \\ \mu_{HoZE}(x) \\ \mu_{HoPB}(x) \end{bmatrix} = \begin{bmatrix} \text{tr}(P(x)(\mu_{NB}(x))^H) \\ \text{tr}(P(x)(\mu_{ZE}(x))^H) \\ \text{tr}(P(x)(\mu_{PB}(x))^H) \end{bmatrix} \quad (10)$$

After processing in each mode fuzzifier module and the linguistic hedge module, the resulting signals are sent to the succeeding stage referred to as the inference engine. This stage infers the fuzzy control actions employing fuzzy implication and rules constructed by the expert experience. The fuzzy reasoning method adopted in the DMLHFLC is Mamdani's minimum operation rule. The final stage is the defuzzifier module whose function is to transfer the signal from the fuzzy set into the real world for obtaining the actual control actions. The widely used centre of gravity method is adopted in the proposed DMLHFLC.

According to the above description, it can be found that the characteristic of this architecture simplifies the complexity of DMLHFLC design. From the viewpoint of DMLHFLC architecture, inserting a linguistic hedge module for the each mode of operation allows us to use the simple triangle like membership functions and a fewer number of rules instead of more complicated membership functions and large number of rules to reach the control goals. As a result, the membership construction and the rule development become simpler.

In DMLHFLC, the linguistic hedge combinations which are difficult to be contributed according to human experience and knowledge, must be tuned. Therefore, in this paper a hybrid GA-SA method is proposed as the search method to acquire an optimal combination of the linguistic hedge. The hybrid GA-SA module works here in offline. That is, it searches the optimal linguistic hedge module to make the DMLHFLC adaptive. Fig. 3 shows the general flow chart of the solution algorithm using hybrid GA-SA method.

4. Design of Controllers

4.1. Design of conventional PI controller and FLC with output feedback

The conventional PI controller with output feedback are designed using maximum stability margin criterion [10] and the feedback gains are $k_p = 14.0$ and $k_i = 1.2$. The conventional FLC is also designed using the method given in [7]. The system output is sampled at the normal sampling rate of two seconds and the controller output is also updated at normal sampling rate [7].

4.2. Design of proposed DMLHFLC with output feedback

Design of proposed DMLHFLC with output feedback scheme is carried out for wind power system. Since the switching limit value ϵ should be greater than the steady state error of the system output $\Delta P_{w\text{tg}}$ with only

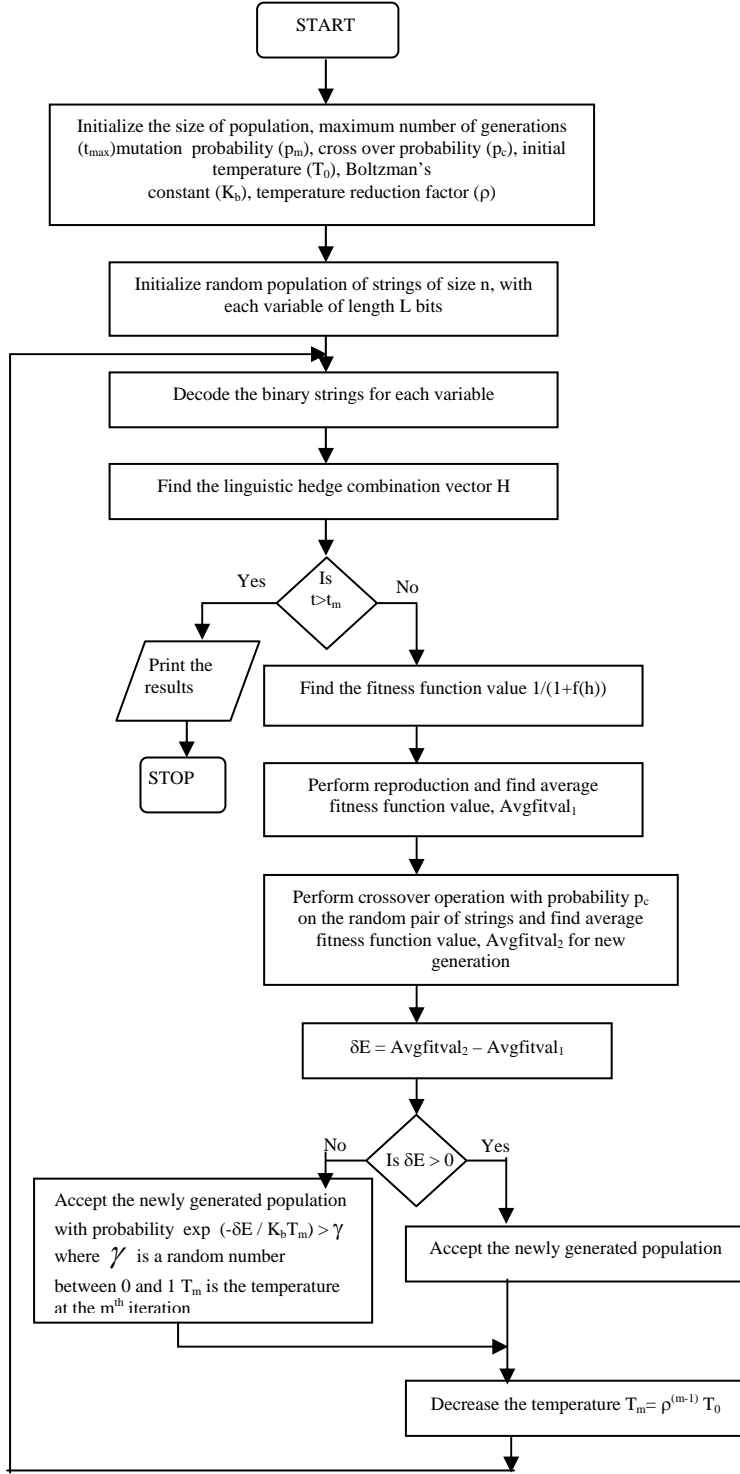


Fig. 3 Flow Chart For hybrid GA-SA method

proportional linguistic hedge fuzzy logic controller, it is chosen as 0.003. The DMLHFLC input variables are ΔP_{wtg}

(error e) and $\Delta \dot{P}_{wtg}$ (change of error ce). Fig. 4 shows the membership functions for the input variables (e and ce) scheduled by only three fuzzy sets with the simple shape membership functions linguistically labeled as NB, ZE and PB distributed over the intervals $e \in [-\alpha, \alpha]$, $ce \in [-\alpha, \alpha]$. The value $\alpha = 0.006$ for fuzzifier module A (proportional type linguistic hedge fuzzy logic controller) and $\alpha = 0.003$ for fuzzifier module B (integral type linguistic hedge fuzzy logic controller). The output variable u is characterized by three fuzzy sets NB, ZE and PB over the interval $[-0.2, 0.2]$ in both modules. The feedback signal is sampled at the normal sampling rate of two seconds and the control output is also updated at normal sampling rate [7].

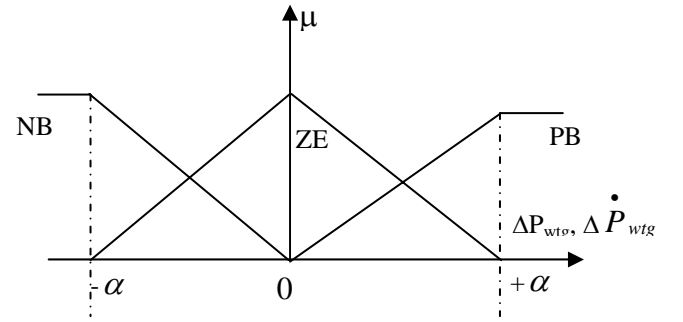


Fig. 4. Membership functions of ΔP_{wtg} and $\Delta \dot{P}_{wtg}$ of wind power system

4.3. Determination of optimal linguistic hedge combination

To obtain the optimal linguistic hedge combination hybrid GA-SA method is used. The number of rules chosen in the DMLHFLC is nine. The domain of each input variable is divided into 8 equal intervals. In this work, the fitness function is chosen using the power scaling function, which can be expressed as

$$f(h) = \exp(-\sigma c_e(h)) \quad (11)$$

where $c_e(h)$ stands for the cost function which varies from problem to problem, and σ can be viewed as a discernment measure. The fitness function expressed in equation (15) is considered and σ is chosen as 0.2. The cost function is chosen as

$$c_e(h) = \sum_{i=1}^m [\Delta P_{wtg_i}(h)]^2 \quad (12)$$

in which m is the number of iterations during simulation.

An appropriate fitness function value is obtained using following equation

$$\text{Fitness} = \frac{1}{1 + f(h)} \quad (13)$$

Hybrid GA-SA method is used as the search method to acquire an optimal combination of the linguistic hedge. The resultant optimal linguistic hedge combination vector is given in Table-I and the parameters of GA-SA are given in Table-II

Table -I. Optimal linguistic hedge combination vector

h_{NB} and h_{PB}	h_{ZE}
0.5 0.5 0.25 0.5 0.5 0.25 0.5 0.5	0.5 0.5 1 0.5 0.5 1 0.5 0.5

Table -II. Parameters of hybrid GA – SA

Total string length	16
Population	10
Maximum generation	50
Crossover probability	0.9
Mutation Probability	0.005
Initial temperature	500
Temperature reduction factor ρ	0.9
Boltzman's constant K_b	0.95

E. Simulation results and observations

The DMLHFLC designed in sections 4.2 and 4.3 is implemented in an isolated wind power system. The performance of this controller is simulated for 0.01p.u. kW step load change and the corresponding wind generator frequency deviation $\Delta\omega_1$, and wind generator power deviation ΔP_{wtg} are plotted as shown in Fig. 5. For easy comparison, the responses of $\Delta\omega_1$, and ΔP_{wtg} of the system with the optimum proportional plus integral controller designed on the basis of maximum stability margin criterion and FLC are also plotted in the same Fig. 5. From the result, it is observed that the proposed DMLHFLC has less overshoot and settling time.

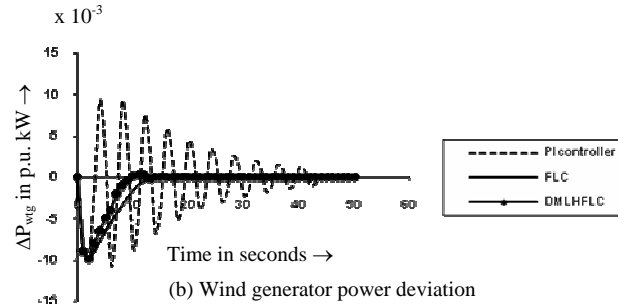
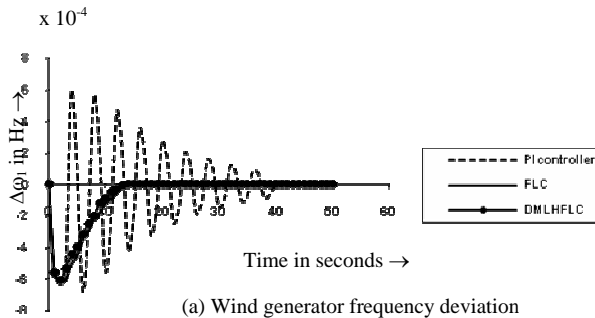


Fig. 5. Comparison of frequency and power deviation of wind power system for 0.01 p.u. kW step load with DMLHFLC, FLC and conventional PI controller

5. Conclusion

This paper presents a new design based on dual mode linguistic hedge fuzzy logic controller to an isolated wind power systems. This design methodology of dual mode linguistic hedge fuzzy logic controller is a hybrid model based on the concepts of dual mode control, fuzzy linguistic hedges and hybrid GA-SA algorithms. Simulation study results of an isolated wind power system reveal that the proposed DMLHFLC provides a high quality transient and steady state response.

Acknowledgement

The authors wish to thank the authorities of Annamalai University, Annamalainagar, Tamil Nadu, India for the facilities provided to prepare this paper.

References

- [1] Skikos, G.D – Machias, A.V: Design and Development of Fuzzy Logic Control Strategies for Wind Turbine Generators, *Wind Engineering* 19 No.5,(1995), 235-248.
- [2] Das, D. – Kothari, D.P: Instability and Dynamics of a wind turbine generator system in an isolated power system, *Journal of Institution of Engineers (India)*, 76, (1995), 69-71.
- [3] Shayeghi, H.- Shayanfar, H.A. - Jalili, A.: Load frequency control strategies: A state-of-the-art survey for the researcher, *Energy Conversion and Management*, Vol.50, No.2, Feb.2009, 344-353.
- [4] Banerjee, S. - J.K. Chatterjee, J.K- S.C. Tripathy, S.C.: Application of magnetic energy storage unit as a load-frequency stabilizer, *IEEE Transactions on Energy Conversion*, Vol-5, No.1, March 1990, 46-51.
- [5] Tripathy, S.C.- Kalantar, M.- Balasubramanian, R.: Dynamics and stability of wind and diesel turbine generations with superconducting magnetic energy storage unit on an isolated power system, *IEEE Transactions on Energy conversion*, Vol. 6, No.4, December.1991, 579-585.
- [6] Gang feng : A survey on analysis and design of model-based fuzzy control systems, *IEEE Transactions on Fuzzy Systems*, Vol.14, No.5, 2006, 676-697.
- [7] Ertugrul Cam.: Application of fuzzy logic controller for load frequency control of hydroelectrical power plants, *Energy Conversion and Management*, Vol.48, 2007, 1281-1288.
- [8] Bin-Da Liu - Chuen-yau Chen - Ju-Ying Tsao : Design of adaptive fuzzy logic controller based on linguistic-hedge concepts and genetic algorithms, *IEEE Transactions on Systems, Man, and Cybernetics- Part B*, Vol.3, No.1, 2001, 32-53.

- [9] Ghoshal, S.P.: Application of GA / GA-SA based fuzzy automatic generation control of a multi-area thermal generating systems, *Electric Power System Research*, Vol.70, 2004,115-127.
- [10] Velusami, S - Chidambaram, I.A.: Decentralized biased dual mode controllers for load frequency control of interconnected power systems considering GDB and GRC non-linearities, *Energy Conversion and Management*, Vol.48, 2007, 1691-1702.

Biographies



M. Mohamed Thameem Ansari (1970) received Bachelor Engineering in Electrical and Electronics Engineering (1992) from Madurai Kamaraj University, Madurai and Master of Engineering in Power System Engineering (1997) from Annamalai University, Annamalainagar. During 1992 – 2007

he was working as Lecturer in the Department of Electrical Engineering, Annamalai University and from 2007 onwards he is working as Reader in the Department of Electrical Engineering, Annamalai University Annamalainagar. He is a life member of Indian Society for Technical Education (ISTE).

He is currently pursuing his Ph.D degree in Electrical Engineering at Annamalai University, Annamalainagar. His research interests are in power systems, application of fuzzy logic, neural network and artificial intelligence to power systems. (Department of Electrical Engineering, Annamalai University, Annamalainagar – 608 002, Tamilnadu, India. Tel:- 91-04144 -239735, Fax: - 91 - 04144- 238275, ansari_aueee@yahoo.co.in)



Professor S.Velusami (1955) received Bachelor of Engineering in Electrical and Electronics Engineering (1978) and Master of Engineering in Power System Engineering (1981) from Annamalai University, Annamalainagar and

Ph.D(1990) from Indian Institute of Technology, Chennai. He received PGDCA (1992) from Madurai Kamaraj University, Madurai and PGDEA(2000) from Institute for Social Science and Research, Vellore. During 1980-1991 he was Lecturer in the Department of Electrical Engineering, Annamalai University from 1992-1994 he was Reader and then from 1994-2000 he was Professor and presently he is working as Professor and Head of the Department of Electrical Engineering, Annamalai University, Annamalainagar. He is a life member of Indian Society for Technical Education (ISTE) and also life member of the Society of Power Engineers (India), the Institute of Engineers (India) and the System Society of India. During his under graduate programme he was awarded as 'Best Student' for his all round proficiency. His research interests are in power systems, electrical machines, application of fuzzy logic, neural network and artificial intelligence to power systems. (Department of Electrical Engineering, Annamalai University, Annamalainagar – 608 002, Tamilnadu, India, Tel:- 91-04144-239735, Fax:-91-04144-238275, (profvels@yahoo.co.in).

Appendix

System Parameters

H_w	= 3.5
K_{fc}	= 16.2 Hz/p.u k.W
ΔP_w	= 0.01 p.u.kW
T_{p1}	= 0.6 sec
T_{p2}	= 0.041 sec
K_{pc}	= 0.08
Base	= 250 kVA

Nomenclature

$\Delta\omega_1$	wind generator frequency deviation in Hz
ΔP_w	wind power disturbance in p.u.kW
ΔP_{wtg}	wind generator power deviation in p.u.kW
H_w	inertia constant of wind system in seconds
s	Laplace complex frequency operator
P_R	area capacity in kW
K_{pc}	blade characteristic gain
K_{FC}	fluid coupling gain
K_{P3}	data fit pitch response gain
K_{P2}	hydraulic pitch actuator gain
K_{P1}	programmed pitch control gain
T_{P1}, T_{P2}	time constants of hydraulic pitch actuator in seconds.
μ	membership value

Superscript

T	Transpose of a matrix
---	-----------------------