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Dual Mode Linguistic Hedge Fuzzy Logic Controller for an Isolated Biomass Based Diesel Wind Hybrid Power System with Battery Energy Storage Unit

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In this paper, a dual mode linguistic hedge fuzzy logic controller for an isolated biomass based diesel wind hybrid power system with battery energy storage unit is proposed. In this fuzzy logic controller design, the linguistic hedge operators are used to adjust the shape of the system membership functions dynamically, and can speed up the control result to fit the system demand. The genetic algorithm-simulated annealing algorithms are adopted to search the optimal linguistic hedge combination in the linguistic hedge module. Dual mode concept is also incorporated in this proposed controller because it can improve the system performance. The system with the proposed controller was simulated and the frequency deviation resulting from a step load disturbance is presented. The simulation results show that the system performance is improved with the proposed controller. It is also found that the controller is less sensitive to the changes in the system parameters.

Keywords: *Biomass Based Diesel Wind Hybrid Power System, Dual Mode Linguistic Hedge Fuzzy Logic Controller, Battery Energy Storage Unit*

NOMENCLATURE

$\Delta\omega_1$	wind generator frequency deviation in Hz
ΔP_{load}	change in load in p.u.kW
ΔP_{wtg}	wind generator power deviation in p.u.kW
H_w	inertia constant of wind system in seconds
H_d	inertia constant of diesel system in seconds
s	Laplace complex frequency operator
ΔP_f	diesel generator power deviation in p.u.kW
P_R	area capacity in kW
$\Delta\omega_2$	diesel generator frequency deviation in Hz
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
T_2	time constant of engine actuator in seconds
T_d	time constant of biomass based diesel engine in seconds
1/R	feedback gain of actuator in p.u. kW
HHV	higher heating of biogas in kcal/kg
PI	proportional plus integral
FLC	fuzzy logic controller

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DMLHFLC	dual model linguistic hedge fuzzy logic controller
BES	battery energy storage
NB	negative big
ZE	zero
PB	positive big
GA-SA	genetic algorithm-simulated annealing
μ	membership value
r_{bp}	self discharge resistance in kilo ohms
c_{bp}	battery capacitance in F
r_{bt}	connecting resistance in ohms
r_{bs}	internal resistance in ohms
r_b	over voltage resistance in ohms
c_b	over voltage capacitance in F

Superscript

T	transpose of a matrix

1.0 INTRODUCTION

Wind energy is widely seen in many countries as the most promising of renewable energy sources. However, the wind power generation has its own characteristics that are different from existing generating units such as the wind dependence caused inconsistency of the prime mover[1]. Hence there is a need for some magic formula such as wind combined with diesel[2,3].

Power generation from biomass has emerged as a very interesting complement to conventional sources of energy because of its contribution to the reduction of the green house effect[4]. The operation of biomass based diesel generator set for extended periods at low power level (less than 50%) could result in possible engine damage together with a reduction in working lifetime. So a simple biomass based diesel generator back-up may not be sufficient and there is a need for reliable energy storage medium.

Battery energy storage has recently emerged as one of the most promising storage technology for use in power system that offers solutions to many operational problems faced by power system [5,6] today.

A number of methods [7,8] are found in the literature for the suitable control of the biomass based diesel wind hybrid power system to achieve improved dynamic performance and extract the maximum benefit out of the available energy. The conventional approach using PI controllers and fuzzy logic controllers [9,10] result in relatively large overshoots in transient frequency deviations. Further, the settling time of a system frequency deviation is also relatively long.

On the other hand, Zadeh proposed the fuzzy linguistic hedges to modify the membership function of the fuzzy sets. By means of adjusting the membership functions and dynamically through the linguistic hedge concept, fewer rules and simple shape membership functions [11] can be employed to achieve a better performance than a conventional FLC.

Therefore, this paper proposes a new design of dual mode linguistic hedge fuzzy logic controller for biomass based diesel wind hybrid power system with battery energy storage unit. An important design concept of dual mode control strategy is incorporated in the proposed control because it improves the system performance [12]. Hybrid GA-SA algorithms are adopted to search optimal linguistic hedge combination vector in the linguistic hedge module. The computer simulation results prove that the proposed controller is effective and provides significant improvement in system performance. Further, it has also been observed that the proposed controller is less sensitive under system parameter variations.

2.0 DEVELOPMENT OF MATHEMATICAL MODEL OF AN ISOLATED BIOMASS BASED DIESEL WIND HYBRID POWER SYSTEM WITH BES UNIT

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 biomass based diesel wind hybrid power

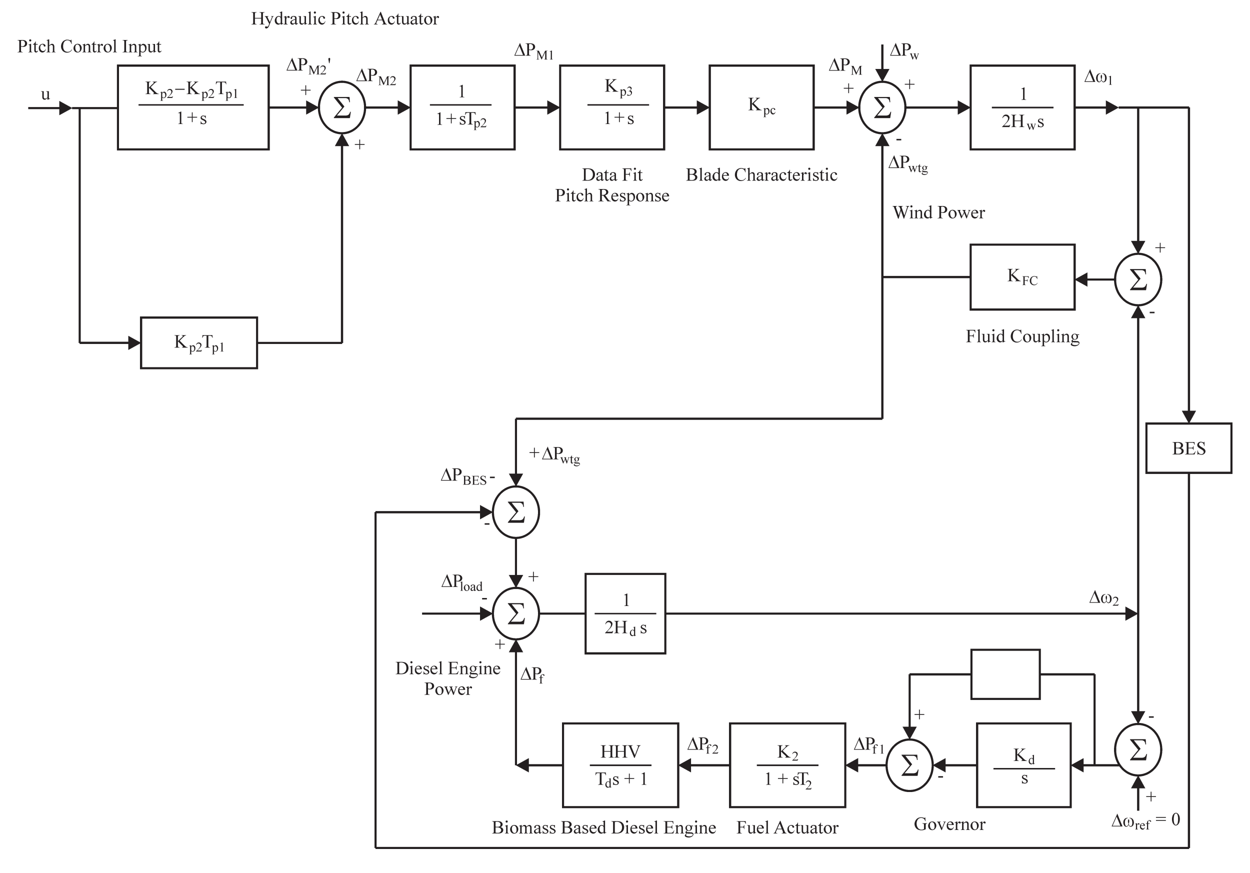


FIG. 1 TRANSFER FUNCTION MODEL BLOCK DIAGRAM OF AN ISOLATED BIOMASS BASED DIESEL WIND HYBRID POWER SYSTEM WITH BES UNIT

system with BES unit is shown in Fig. 1 [8]. It consists of a pitch controlled wind turbine and equipped with an induction generator connected to an ac bus-bar in parallel with a biomass based diesel generator set consisting of a diesel engine driving a synchronous generator, and BES unit.

The main components of the BES facility are, an equivalent battery composed of parallel series connected battery cells, a 12-pulse cascaded bridge circuit connected to a y / -y transformer and a control scheme. The incremental BES model as shown in Fig. 2.

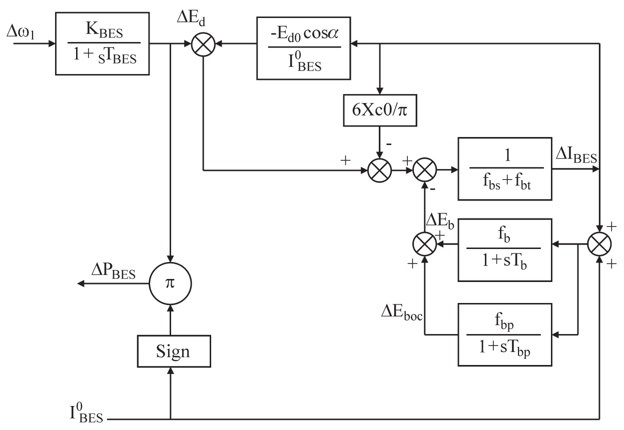


FIG. 2 BLOCK DIAGRAM OF AN INCREMENTAL BES MODEL

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

$$\dot{\underline{x}} = \underline{A}x + \underline{b}\,\underline{u} + \underline{\gamma}\,\underline{d} \tag{1}$$

$$\underline{y} = \underline{C}\underline{x} \tag{2}$$

Where,

$\underline{x}$ = $[\Delta w_1, \Delta P_M, \Delta P_{M1}, \Delta P_{M2}', \Delta w_2, \Delta P_f, \Delta P_{f2}, \Delta P_{f1}, \Delta E_d, \Delta E_{boc}, \Delta E_b]^T$ is the 11th order state vector.

$\underline{d}$ = $\Delta P_{load} + I^0_{BES}\,\Delta E_d$, I^0_{BES} is the scalar disturbance input

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

$\underline{y}$ = ΔP_{wtg} is the scalar output

ΔE_d, ΔE_{boc} and ΔE_b are the state variables of the battery unit. Other state variables are marked in Fig. 1.

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.

3.0 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 (1) is augmented with a new state variable defined as the integral of ΔP_{wtg} ($\int \Delta P_{wtg} dt$). The augmented system of 12th order can be described as

$$\dot{\underline{x}} = \bar{A}\underline{x} + \bar{b}\,\underline{u} + \bar{\gamma}\,\underline{d} \tag{3}$$

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

$$\bar{A} = \left[\begin{array}{c:c} 0 & \underline{C} \\ \hdashline 0 & \underline{A} \end{array}\right], \quad \bar{b} = \left[\begin{array}{c} 0 \\ \hdashline \underline{b} \end{array}\right] \quad and \quad \bar{\gamma} = \left[\begin{array}{c} 0 \\ \hdashline \underline{\gamma} \end{array}\right]$$

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

$$\bar{y} = \bar{C}\,\bar{x} \tag{4}$$

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

$$\bar{C} = \left[\begin{array}{c:c} 1 & 0 \\ \hdashline 0 & \underline{C} \end{array}\right]$$

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,

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

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

$$u = k^T \bar{y} \tag{5}$$

to meet the desired output response of the system.

The control law equation (5) can be written interms of ΔP_{wtg} as

$$u = -k_I \int \Delta P_{wtg} dt - k_P\ \Delta P_{wtg} \tag{6}$$

where $k^T = [-k_I,\ -\ k_p]$ is a 2-dimensional conventional integral and proportional controller constant feedback gain vector.

Unfortunately, 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. Therefore, many controllers with fuzzy logic approach are proposed in literature [9].

The control law (5) is replaced by a conventional fuzzy controller [10]. In the conventional fuzzy controller, the error signal DP_{wtg} is obtained at every sampling time step, fed into the fuzzy algorithm, where the change in error signal of DP_{wtg} and the value of control action u are evaluated from a set of conditional statements. This value of the control action is then fed into the system and the procedure is repeated at every time step.

The constant gain output feedback controller and the fuzzy logic controller with output feedback are used in this study as the benchmark for comparison with the proposed controller.

4.0 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 [12], 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 [13].

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. 3 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.

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

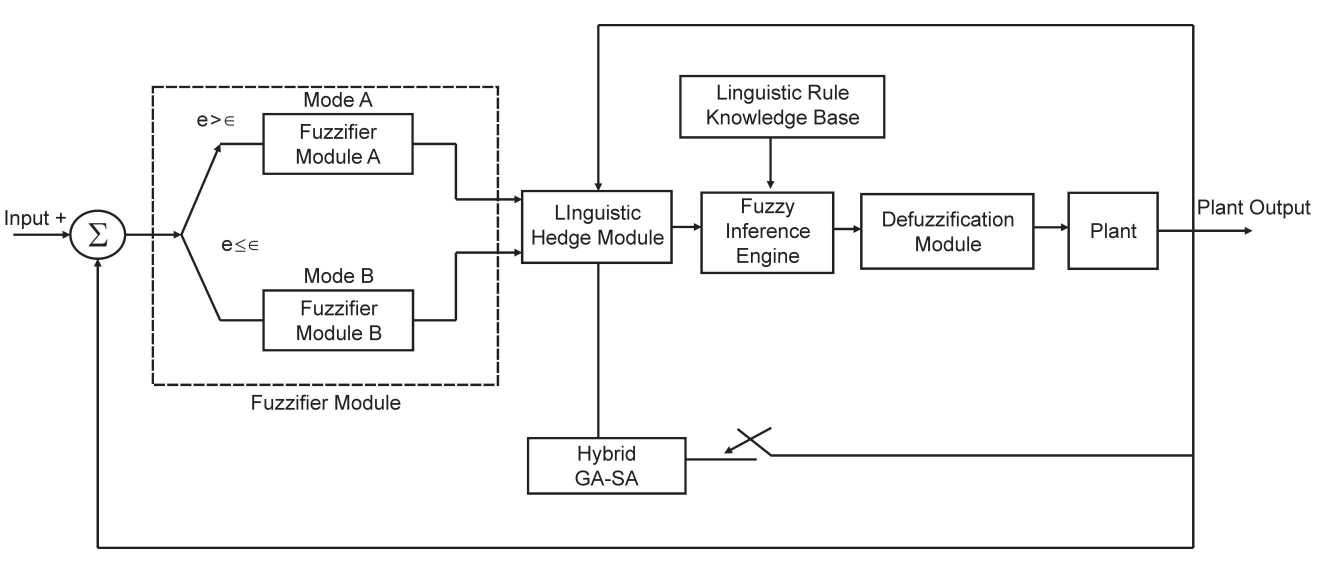


FIG. 3 BLOCK DIAGRAM OF DUAL MODE LINGUISTIC HEDGE FUZZY LOGIC CONTROLLER

adaptive. The general flowchart of the solution algorithm using hybrid GA-SA method is given in Fig. 4.

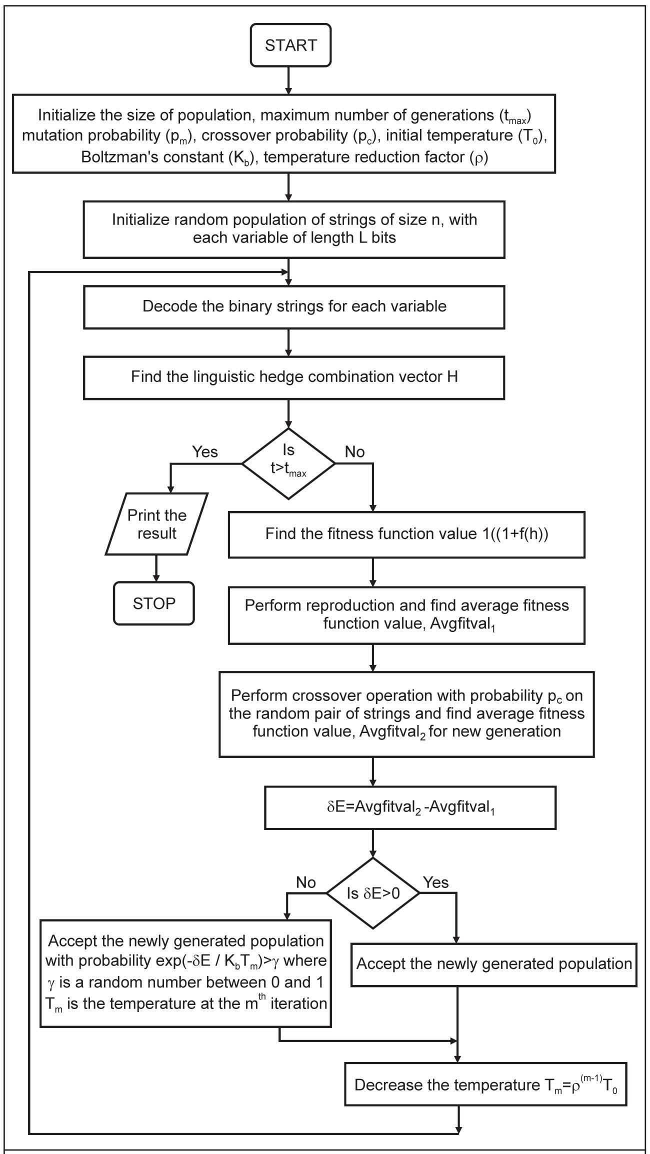


FIG. 4 FLOWCHART FOR HYBRID GA-SA METHOD

5.0 APPLICATION OF PROPOSED DUAL MODE LINGUISTIC HEDGE FUZZY LOGIC CONTROLLER FOR AN ISOLATED BIOMASS BASED DIESEL WIND HYBRID POWER SYSTEM WITH BES UNIT

5.1 Development of Mathematical Model

The proposed DMLHFLC is applied to an isolated biomass based diesel wind hybrid power system with BES unit. Data for the system is taken from [5, 8] and the matrices and are given in Appendix.

5.2 Design of Conventional PI Controller and FLC with Output Feedback

The conventional PI controller with output feedback are designed using maximum stability margin criterion [14] and the feedback gains are $k_p = 4.0$ and $k_1=1.4$. The conventional FLC is also designed using the method given in [10]. The system output is sampled at the normal sampling rate of two seconds and the controller output is also updated at normal sampling rate [10].

5.3 Design of Proposed DMLHFLC with Output Feedback

Design of proposed DMLHFLC with output feedback scheme is carried out for biomass based diesel wind hybrid power system with BES unit. Since the switching limit value $\in$ should be greater than the steady state error of the system output ΔP_{wtg} with only proportional linguistic hedge fuzzy logic controller, it is chosen as 0.00035. The DMLHFLC input variables are ΔP_{wtg} (error e) and $\Delta\dot{P}_{wtg}$ (change of error ce). Fig. 5 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 $\varepsilon \in [-\alpha, \alpha]$, $ce \in [-\alpha, \alpha]$. The value $\alpha = 0.0006$ for fuzzifier module A and $\alpha = 0.00035$ for fuzzifier module B. The output variable u is characterized by three fuzzy sets NB, ZE and PB over the interval [-0.04, 0.04]. The feedback signal is sampled at the normal sampling rate of two seconds and the control output is also updated at normal sampling rate [10].

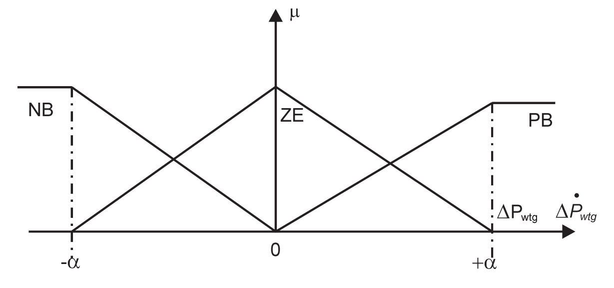


FIG. 5. MEMBERSHIP FUNCTIONS OF DP_{WTG} AND D OF WIND-DIESEL HYBRID POWER SYSTEM WITH BES UNIT

5.4 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

$$f(h) = \exp(-\sigma c_e(h)) \quad (7)$$

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

$$c_e(h) = \sum_{i=1}^{m} [\Delta P_{wtg_i}(h)]^2 \quad (8)$$

in which m is the number of iterations during simulation.

An appropriate fitness function value is obtained using following equation

$$\text{Fitness} = \frac{1}{1+f(h)} \quad (9)$$

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 1 and the parameters of GA-SA are given in Table 2.

TABLE 1

OPTIMAL LINGUISTIC HEDGE COMBINATION VECTOR

h_{NB} and h_{PB}								h_{ZE}							
0.5	1	1	1	1	1	1	0.5	0.5	1	1	2	2	1	1	0.5

TABLE 2

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

5.5 Simulation Results and Observations

In order to examine the performance of the proposed controller applied to an isolated biomass based diesel wind hybrid power system with BES unit, a series of computer simulation studies were carried out for 0.01 p.u. kW step load change and the results are shown in Fig. 6. For easy comparison, the responses of $\Delta\omega_1$, $\Delta\omega_2$,

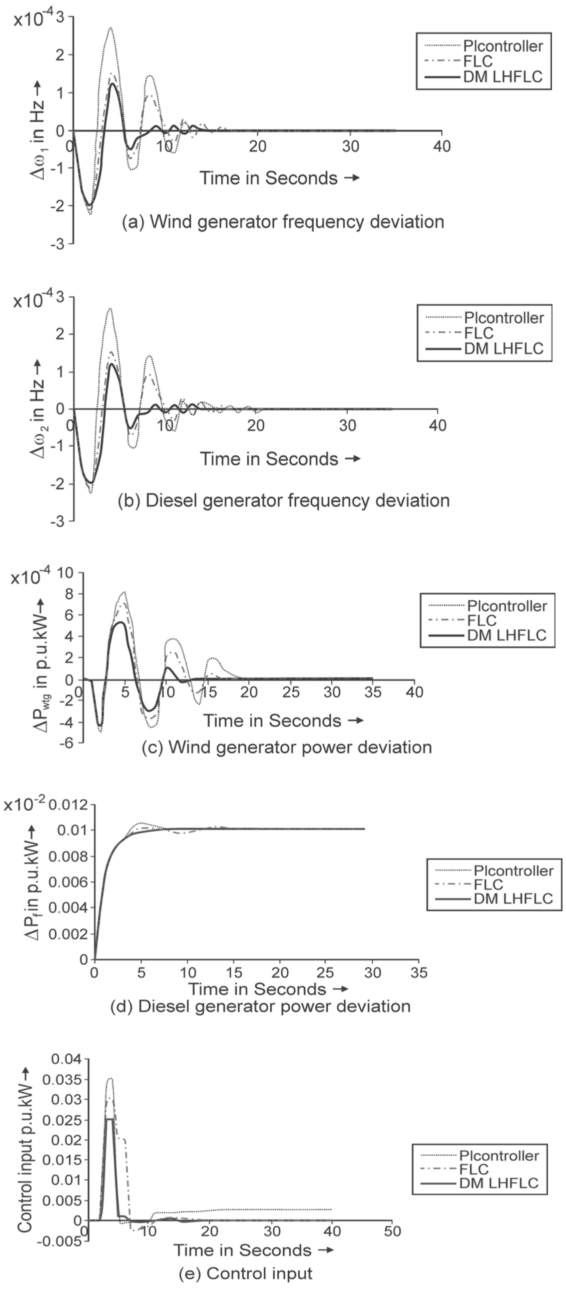
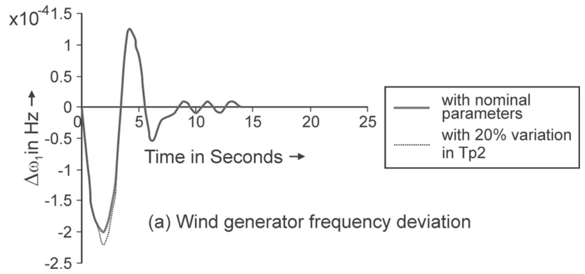


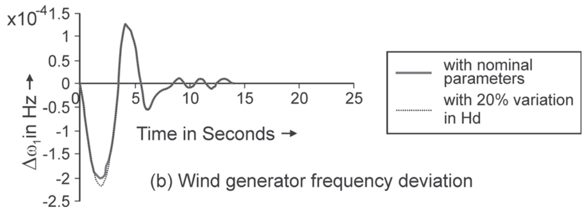
FIG. 6. COMPARISON OF FREQUENCY, POWER DEVIATION AND CONTROL INPUT OF BIOMASS BASED DIESEL WIND HYBRID POWER SYSTEM WITH BES UNIT FOR 0.01 P.U. kW STEP LOAD CHANGE WITH DMLHFLC, FLC AND CONVENTIONAL PI CONTROLLER

ΔP_{wtg}, ΔP_f of the system with the optimum PI controller and FLC are also plotted in the same Fig. 6. From the result, it is observed that the proposed DMLHFLC has less overshoot and settling time.

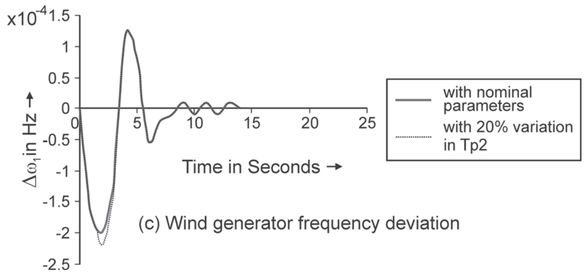
Sensitivity is considered an important factor for any control algorithm. Therefore, the performance of the proposed controller has been analyzed under parameter variation of the system. The parameters T_{p2}, H_d and H_w are varied by 20% from the nominal value one at a time, and simulations are carried out. The simulation results are shown in Fig. 7. From the results, it is found that the proposed DMLHFLC is less sensitive to parameter variation.



(a) Wind generator frequency deviation



(b) Wind generator frequency deviation



(c) Wind generator frequency deviation

FIG. 7 COMPARISON OF WIND GENERATOR FREQUENCY DEVIATION FOR 0.01 P.U. kW STEP LOAD CHANGE WITH SYSTEM PARAMETER VARIATION

6.0 CONCLUSION

This paper presents a design of dual mode linguistic hedge fuzzy logic controller to an isolated biomass based diesel wind hybrid power system with battery energy storage unit. This design takes advantage of the superior characteristics inherent in the linguistic hedges and the search ability of GA-SA. Dual mode concept is included in the proposed controller in order to improve the system performance. Simulation study results of an isolated biomass based diesel wind hybrid power system with BES unit reveal that the proposed controller provides a high quality transient and steady state responses.

7.0 ACKNOWLEDGEMENT

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APPENDIX

$$\bar{A}_{11} = \begin{bmatrix} 0 & 16.2 & 0 & 0 & 0 \\ 0 & -2.3143 & 0.1429 & 0 & 0 \\ 0 & 0 & -1 & 0.112 & 0 \\ 0 & 0 & 0 & -24.3902 & 24.3902 \\ 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$

$$\bar{A}_{12} = \begin{bmatrix} -16.2 & 0 & 0 & 0 \\ 2.3143 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}; \ \bar{A}_{13} = [0]_{(5x3)}$$

$$\bar{A}_{21} = \begin{bmatrix} 0 & 0.9529 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & -9.5294 & 0 & 0 & 0 \end{bmatrix}$$

$$\bar{A}_{22} = \begin{bmatrix} -0.9529 & 0.0588 & 0 & 0 \\ 0 & -1.8182 & 1.8182 & 0 \\ 0 & 0 & -5.0 & 5.0 \\ 7.5294 & -.5882 & 0 & 0 \end{bmatrix}$$

$$\bar{A}_{23} = [0]_{4x3} \ ; \ \bar{A}_{31} = \begin{bmatrix} 0 & 15.2269 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\bar{A}_{32} = [0]_{(3x4)}\,;\ \bar{A}_{33} = \begin{bmatrix} -184615 & 0 & 0 \\ 0.245 & -0.245 & -0.245 \\ 0.0129 & -0.0129 & -22853 \end{bmatrix}$$

$$\bar{b}^{T} = [0\ \ 0\ \ 0\ \ 18.2927\ \ 0.5\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0]$$

$$\bar{\gamma} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -0.0588 \\ 0 \\ 0 \\ 0.882 \\ 0 \\ 0.00004 \\ 2.0226 \end{pmatrix} \;;\quad \bar{C}^{T} = \begin{pmatrix} 1 & 0 \\ 0 & 16.2 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -16.2 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}$$

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