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Fuzzy-PI Based Frequency Regulation in Wind-Thermal Hybrid System

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Abstract— **This paper presents fuzzy tuned-PI controller to minimize the frequency deviations in a hybrid distributed generation system consisting of wind-thermal along with storage system flywheel energy storage system (FESS) and ultracapacitors. The frequency deviation in the hybrid system in the presence of the controllers like conventional-PI and fuzzy-PI is compared under the presence of FESS/UC under different disturbance scenarios. Step as well as random variation in wind speed and load demand are considered as disturbance input to the above hybrid system. In addition to the graphical results, comparison in terms of the performance indices, settling time, peak overshoot, integral square error (ISE) is also presented. Both graphical and quantitative results clearly show the robustness and better performance of fuzzy based PI controller as compared to the conventional PI for minimization of frequency deviation in hybrid power system.**

Keywords— **Energy storage system, flywheel energy storage system (FESS), frequency regulation, fuzzy controller, hybrid system, PI Controller, ultracapacitors (UC).**

I. INTRODUCTION

In recent years, small scale power generation techniques in the form of distributed generation (DG) is gaining increasing attention and popularities by the engineering as well as business communities. DG can be used as stand-by to the centrally generated electric power during peak load and can either be connected to the power grid or run in isolated/stand-alone mode of operation. Use of DG can make-up the increasing energy demand and power crisis due to depletion coal, petrol, diesel etc, at a faster rate due to increasing urbanization and industrialization. Among the DG, renewable energy resources such as wind, solar, tidal, geothermal, fuel cell etc. are gaining popularity as per location and requirements. Wind and solar energy has been identified as the most useful source for exploration of electric power and has got wide spread applications because of its environment friendliness, low cost and development of the related technology. But, they suffer from the intermittent characteristic depending upon the climatic conditions. Thus, these sources are integrated with the conventional power from thermal, hydro, diesel generator, nuclear along with the energy storage devices such as flywheel energy storage (FESS), battery energy storage system (BESS), ultracapacitors (UC) etc. for improving the performance of the power system [1]. A wind-thermal or wind-thermal-hydro when integrated with FESS/BESS/UC becomes more reliable because the hydro system being a locally reliable source that provides an alternative to get an average power to the consumers far away from thermal station. The wind power is an additional advantage where the mini-hydro or micro-hydro alone cannot meet the load demand.

But the major setback is the variation in wind speed, solar radiation along with the change in load leading to an active power mismatch between power generation and the load demand. This subsequently leads to variation in frequency profile from the nominal value. As a result of the frequency deviation in the hybrid system, the stability and control of operation is greatly affected and therefore must be taken care by use of some sophisticated controller so that the frequency deviation remains within a safe/desired limit.

In literature many methods and controller are available to minimize the above mentioned problem. The most simple being the PI/PID controller [2] which usually suffers from the heuristic selection of its gain constants that leads to more oscillatory response. Therefore authors have been designed knowledge based fuzzy logic controller (FLC) controllers for improving the frequency profile [3].

This paper applied fuzzy based controller to tune the gains of the conventional-PI controller, i. e., K_p and K_i. The main objectives in the proposed study is described as follows :

a) To study the interconnections of wind, thermal, FESS and UC.
b) To tune the PI controller gain by using fuzzy controller.
c) Optimize the dynamic response of this hybrid system for attaining zero frequency deviation under step/random change in wind speed and load demand.
d) To compare the performance of conventional-PI and fuzzy-PI controller for minimizing the system frequency deviation, both graphically as well as in terms of performance indices such as peak overshoot, settling time and ISE.

Section II presents the modelling of the components of the hybrid system followed by optimization using fuzzy and neuro-fuzzy controller described in Section III. Then, Section IV describes the simulation results obtained by using MATLAB/Simulink software. Finally, the conclusions obtained from the current study is presented in Section V.

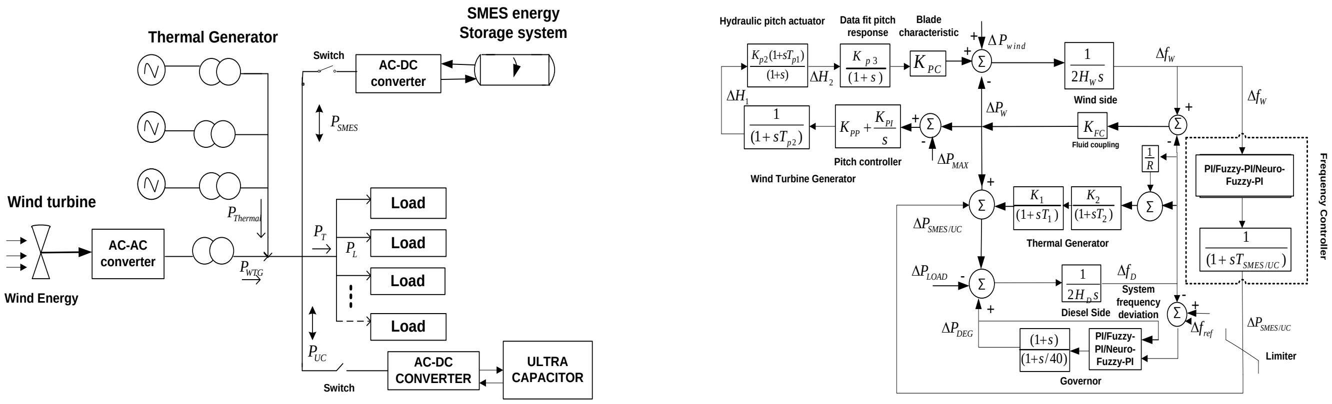


Fig.1 Block diagram of the hybrid distributed generation system (a) system integration (b) system transfer functions.

II. SYSTEM MODELLING

In the modelling of the hybrid system, certain assumptions have been made and non-linearity of the various system components has not been considered to reduce the complexity in modeling [4]-[5]. Step and random inputs in the form of wind speed and load demand are used for the hybrid power system developed in MATLAB/Simulink. The block-diagram and transfer function diagram for the hybrid system is shown in Fig. 1 where the resources are connected in parallel to supply the load demand. The energy storage in the form of FESS and UC are also integrated with the offshore wind farm in order to store/supply the surplus/deficient power as per the load requirements. The details of the nomenclature and parameters used in this proposed study is presented in Table IV of the appendix section. The modeling of the sub-systems are briefly described below:

(a) Wind-Turbine Generating Unit (WTGU)

It consists of a step input to the wind turbine which replicates the wind speed variations. The turbulence factor has been neglected. The mechanical power generated from the wind turbine is given as [2] :

$$P_w = \frac{1}{2}\rho A C_p V^3 \tag{1}$$

Where ρ is the air density (kg/m^3), A=area swept by the blade (m^2), C_p is the power co=efficient which is the function of tip-speed ratio (λ) and blade pitch angle (β). The transfer function of the WTGU is given by a linear first order lag [2]:

$$G_{WTGk}(s) = \frac{K_{WTGk}}{1+sT_{WTGk}} = \frac{\Delta P_{WTGk}}{\Delta P_W},\ \ k=1,2 \tag{2}$$

Where K_{WTG} is the gain constant and T_{WTG} is the time constant and P_{WTG} is the electrical power of WTGU. This unit is also provided with storage systems based on FESS which is an electro-mechanical system where the energy is stored in the form of inertia due to the kinetic energy of the rotating free-wheel. Similarly, UC are electrochemical type capacitors which offer large capacitances in the order of thousands of farads at a low voltage rating of about 2.5V. They are used to store electrical energy during surplus generation and deliver high power within a short duration of time during the peak-load demand. Both FESS and UC units are taken in linear form [2]. Similarly the thermal sub-units are considered to be first order linear systems [6].

III. TUNING OF PI GAINS BY FLC/NFLC

Fuzzy Expert System (FES) primarily consists of four steps namely knowledge base/rule base, fuzzy inference engine, fuzzification and defuzzification. A set of appropriate if-then rules are designed for mapping the input to output and depending upon this, appropriate decisions are developed. Fuzzy Inference Mechanism involves membership functions, fuzzy operators and if-then rules. Then fuzzification followed by defuzzification steps are implemented to convert crisp value to fuzzy and vice versa [7]-[8]. Usually, three types of techniques like Mamdani, Sugeno and Tsukamato are used to design a fuzzy controller. Of course we have used the Mamdani type in our current study of frequency deviation in hybrid distributed generation system. It also works well with human inputs and that is why we have used it in our inference engine [9]-[10]. The FLC/NFLC as shown in Fig. 1 is designed in this section representing the fuzzy rulesas given in Table I. The fuzzy controller with the block diagram for tuning PI controller is shown in Fig. 2 and 3.

Membership Functions- Appropriate number of variables must be used to clearly denote the rules and with suitable ranges so that there is a trigger for every oscillation of the *err* values and *del-err* values. Five membership variables for each input variable viz. NB, NS, ZZ, PS, PB have been used. Similarly, for output variables the choice of membership functions has been S, M, B, VB, VVB.

The input and output membership functions considered in the fuzzy controller design are considered as triangular type. Also the fuzzy rules are represented in Table I.

Scaling Factor-The FIS system consists of four variables where *err* and *del-err* are taken as inputs to produce outputs as K_p and K_i for the tuned PI controller by using the rules stated above. Hit and Trial method is adopted to obtain the different values of parameters in model.

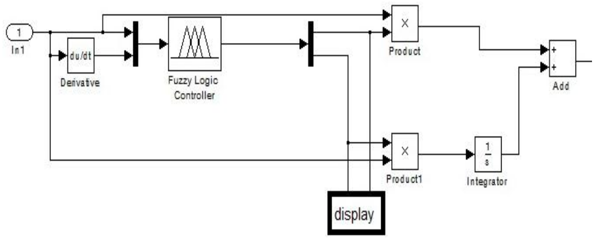


Fig. 2 FLC.

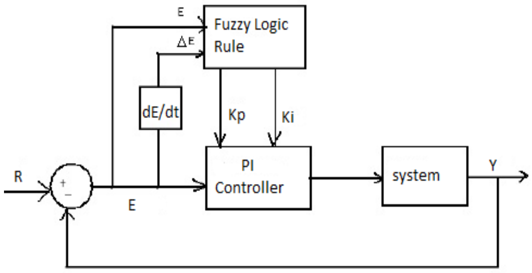


Fig. 3 Block diagram of a fuzzy based PI controller.

TABLE I
FUZZY RULES FOR PI GAINS TUNING

E/ΔE	NB	NS	ZZ	PS	PB
NB	S	S	M	M	B
NS	S	M	M	B	VB
ZZ	M	M	B	VB	VB
PS	M	B	VB	VB	VVB
PB	B	VB	VB	VVB	VVB

Rule Editor Kp

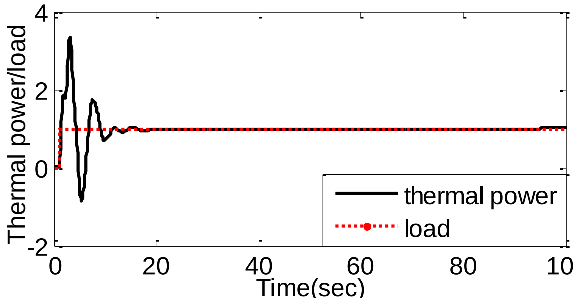
E/ΔE	NB	NS	ZZ	PS	PB
NB	S	S	M	M	B
NS	S	M	M	B	VB
ZZ	M	M	B	VB	VB
PS	M	B	VB	VB	VVB
PB	B	VB	VB	VVB	VVB

Rule Editor Ki

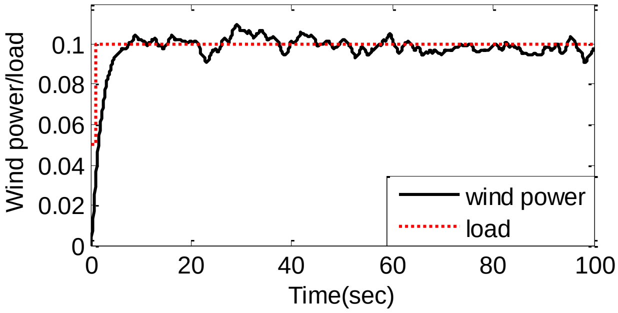
IV. SIMULATION RESULTS

A. *Time-domain study*

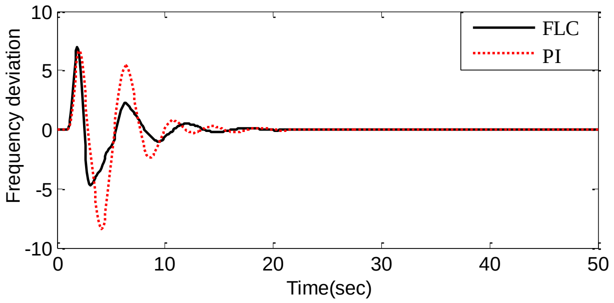
The wind-hydro-thermal hybrid system is formulated in MATLAB/SIMULINK and frequency deviation is analysed for step change in load demand. The improvement in frequency deviation is studied in the presence of two different controllers namely the conventional PI-controller and fuzzy-PI controller. The input wind speed to the wind energy system is considered to be random in characteristics which varies within ± 10 % of the nominal wind speed of 10 m/sec. The simulation study represented in Fig. 4 (a)-(c) shows the variation of thermal and wind system output power with reference to the individual load demand variation. The individual unit output power is controlled by the conventional PI and fuzzy-PI controller in order to fulfil the change in load demand. The values of K_p and K_i in conventional PI controller were determined on the basis of a heuristic approach which later turned out to be tedious process given the scenario of more than two interconnected power systems. Therefore to enhance the performance, fuzzy logic controller (FLC) is designed to tune the PI gains.



(a) Thermal power vs load



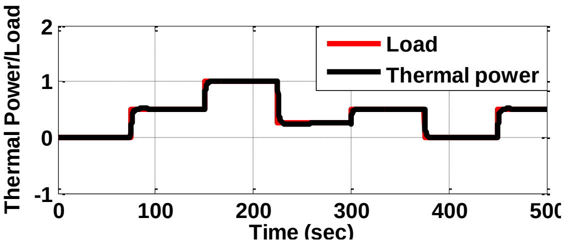
(b) Wind power vs load



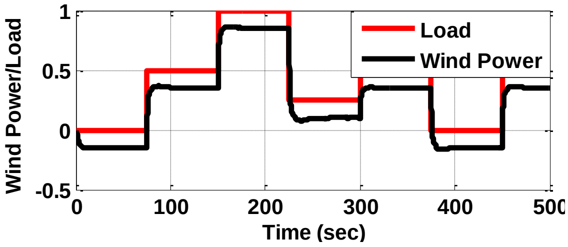
(c) Frequency deviation in presence of PI and fuzzy controller.

Fig. 4 Power and frequency variations in the hybrid system for step change in wind speed.

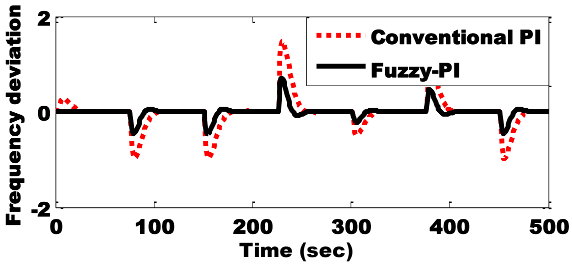
Similarly, the variation in thermal and wind power foollowed by the frequency deviation in presence of both the above two controller is represented in Fig. 5 (a)-(c) under step variation in load demand. Again, the frequency deviation on the hybrid power system is also studied under the random variation in wind speed. It is observed that the fuzzy based PI controller work nicely and robustly to a large variation in wind speed as disturbance input to the system. The results are shown in Fig. 6 (a) and (b).



(a) Thermal power vs load

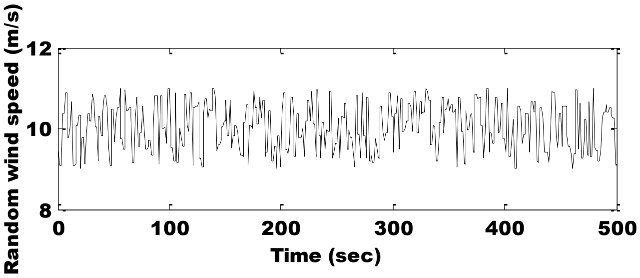


(b) Wind power vs load

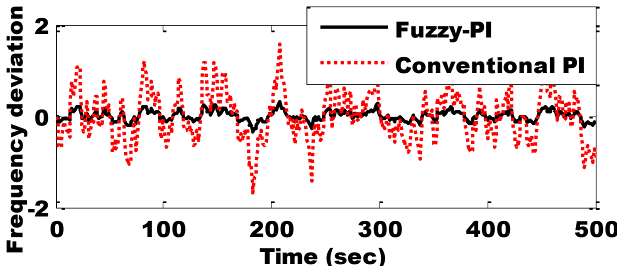


(c) Frequency deviation.

Fig. 5 Power and frequency variations in the hybrid system for step change in load demand.



(a) Random variation of wind speed.



(b) Frequency deviation.

Fig. 6 Frequency variations in the hybrid system for random change in wind speed.

A comparative result for the deviation of system frequency is represented in Fig. 5 (g), which clearly shows the better performance of fuzzy-PI controller as comparison to the conventional PI controller. Further the performance indices such as peak overshoot and settling time is computed for both the above controllers and is represented in Table II and III. The study of the calculated values in table shows that the settling time in the presence of fuzzy-PI controller is less as compared to the conventional PI controller, though sometimes the peak overshoot is slightly greater.

TABLE II
FUZZY BASED PI CONTROLLER

	K_p	K_i	t_s	+P	ISE	
Δf1	0.651	2.2	30	0.9	-1.8	0.54
P1	3.11	8.0	32	2.9	0	0.98
Δf2	1.54	4.87	28	5	-8	0.67
P2	9.2	1.01	145	1.9	-1.25	0.77

TABLE III
PI CONTROLLER WITH INTUITIVE VALUES

	K_p	K_i	t_s	+P	-P
Δf1	0.5	1.5	45	1.8	-2.25
P1	0.5	1.5	40	3.4	-0.8
Δf2	0.5	1.5	37	9.2	-8.7
P2	0.5	1.5	182	2.4	-1.7

B. *Frequency-domain study*

To investigate further, the effect of UC in improvement of transient response and suppression of frequency deviation, the controller design has been analyzed through frequency-domain study. Singular value plot in presence of conventional PI and fuzzy-PI controller in corporation with ultracapacitors as storage unit is shown in Fig. 7. An decrease in singular value in fuzz-PI shows the improvement of transient stability with use of UC in hybrid system.

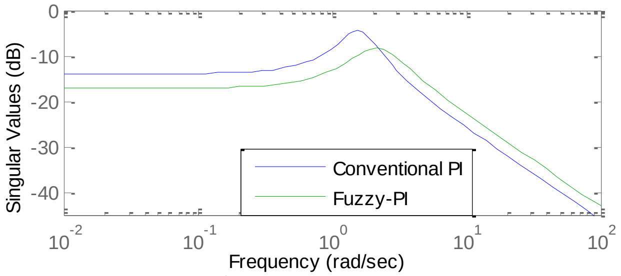


Fig. 7. Singular plot of DG system with SMES and UC

Next, frequency-domain characteristics of the studied hybrid system using eigenvalues and participation factors are presented. These analysed results are very useful to check small-signal stability of the studied hybrid system under steady-state operation. According to the linearized state-space system equations derived in, the system eigenvalues of the studied system can be solved by the following equation:

$$\det(\lambda[I]-[A])=0 \tag{3}$$

where $\det(.)$ denotes the determinant operation of '·', λ is one of the system eigenvalues, $[A]$ is the system matrix, and $[I]$ is an identity matrix having the same dimensions as $[A]$.

A participation matrix $[P]$ can be employed to identify the relationship between the selected state variables and the calculated eigenvalues of the studied system. The participation matrix combines both right and left eigenvectors of $[A]$ as a measure to analyse the association between state variables and eigenvalues. The participation matrix $[P]$ is expressed by (4).

$$[P]=[p_1.........p_n]$$

$$p_i=\begin{bmatrix} p_{1i} \\ p_{2i} \\ \vdots \\ p_{ki} \end{bmatrix}=\begin{bmatrix} \phi_{1i}\varphi_{i1} \\ \phi_{2i}\varphi_{i2} \\ \vdots \\ \phi_{ki}\varphi_{ik} \end{bmatrix} \tag{4}$$

Where ϕ_{ki} is the element on the *k*th row and *i*th column of the modal matrix $[\phi]$ and it is also the *k*th entry of the right eigenvector ϕ_i while φ_{ki} is the element on the *i*th row and *k*th column of the modal matrix $[\varphi]$and it is also the *k*th entry of the left eigenvector φ_i . Table IV lists the eigenvalues of the studied hybrid system with SMES and UC storage units. Incorporating the UC storage unit in the DG system, relatively shifts the location of eigenvalue to the left side of s-plane, thereby enhancing the damping. The overall performance is improved.

TABLE IV

EIGENVALUES OF HYBRID DG SYSTEM

Control Variable	SMES	UC
λ_1	-14.878	-13.464
λ_2	-18.787	-19.551
λ_3	-13.173	-13.940
λ_4	-7.0468 - 6.2326i	-8.0996 - 7.770i
λ_5	-14.895 - 12.6026i	-15.7846 - 13.8270i
λ_6	-11.0621 - 13.629i	-11.4728 - 14.9331i
λ_7	-4.781 - 8.9780i	-5.4728 - 9.8431i
λ_8	-11.873	-12.0348
λ_9	-8.581	-11.0983
λ_{10}	-4.674	-8.041

V. CONCLUSION

An Artificially Intelligent designing method based on Fuzzy Logic has been used, to tune the gains of conventional PI, to minimize the frequency deviation in the hybrid system. It is observed from the graphical as well as the performance indices such as peak overshoot and settling time that fuzzy logic based PI-controller performs better as compared to the conventional PI-controller. Hence the frequency deviation improves in the case of fuzzy controller.

APPENDIX

TABLE IV

PARAMETERS OF THE HYBRID SYSTEM

K_{WTG}	1	T_{FESS}	0.1
T_{WTG}	1.5	K_{BESS}	-0.003
K_{HDVC}	0.005	T_{BESS}	0.01
T_{HDVC}	0.7	B1	-0.5
K_{FESS}	-0.01	R1	0.5
B	-1	P_1	4
B2	-0.5	P_2	4
B3	0.0031	Q_1	1
K_1	0.08	Q_2	26
K_2	0.3	R_1	5
K_3	10	R_2	5
K_4	5	P_3	0.5
D	0.03	P_4	-1
M	0.4		

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