Fuzzy based Power Flow control of Two Area Power System

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ABSTRACT

This paper deals with the novel approach of fuzzy based power flow control of two area power system. Interconnected operation enables utilities to share the generation from one area to other areas. In each area, all the generators are synchronized at same frequency. The change in system load within the area causes frequency deviation in the generating buses and tie line error in the tie lines connecting neighboring areas. The control of interconnected power system is achieved by Automatic Generation Control (AGC), which maintains the balance between generation and load. In this paper, the components of AGC, frequency deviation (ΔF), tie line error (ΔP_{tie}) and the output change in generations (ΔP_{gi}) are calculated by steady state power flow analysis using decoupled Newton Raphson method. The control action is performed by conventional method using participation factor and Fuzzy Logic Controller (FLC). The ΔF and ΔP_{tie} are the inputs to the conventional controller and Fuzzy Logic Controller (FLC). The proposed method is tested with modified IEEE 30 bus system and the results are compared. Analysis reveals that FLC is quite capable of suppressing the frequency deviation and tie line error effectively as compared to that obtained with conventional controller.

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1. INTRODUCTION

An interconnected power system consists of several pools, stations and generators. The method of controlling the real power is carried out by the decisions and actions of engineers. In recent days, the computers are used to control and allocate the generation to load. It is performed automatically based on a continuous load flow calculation by computers. Any deviation in the system frequency is the sensitive indicator of real power imbalance [1]. Automatic Generation Control (AGC) is one of the ancillary services that have become important in the deregulated power system environment [2] to share the load between interconnected areas. M.Okamura and S.Hayasai [3] introduced frequency dependent system component and load frequency controls in the steady state power flow model. Also, the generation and load characteristics were incorporated in the load flow model in such a way that it can be easily adopted for AGC of interconnected power systems. In [4], Fuzzy Logic Controller is developed and tested for automatic generation control, in which ACE is an input to the Fuzzy Logic Controller and simple singleton method is used for finding the generation as output. The use of fuzzy intelligent technique makes the controller well suited for real time application [5]. The calculation of frequency deviation and tie-line error are performed by using De-coupled Newton-Raphson method as given in [6]. Dos Santos, J.L.R.Pereira and De Oliveira [7], used Newton Raphson method for the calculation of Area Interchange Control (AIC) of interconnected power system in which the effect of AIC is represented internally into Jacobian matrix. The authors of papers had developed and applied a rugged model to calculate ACE of an Interconnected Power System.The method constructing membership function for fuzzy logic controller is discussed in [8,9 and 10]. Any deviation in frequency and tie-line power flow is usually represented as static Area Control Error (ACE). Indices for evaluating AGC performance under both simulation and real operation are presented by I.Egido, F. Fernandez-Bernal and L.Rouco in [6].

In this paper, tie-line power flow is controlled by using fuzzy logic controller which can be used in deregulated power system. The steady state power flow analysis is performed using decoupled Newton Raphson method for the calculation of frequency deviation (ΔF) and tie line error (ΔP_{tie}). These are given as an input to the fuzzy logic controller. The existence of ACE shows that there is an excess or deficiency of generation in control area and tie line power flow. The values of generation have to be adjusted by a small amount (ΔP_g) on each unit to minimize frequency deviation (ΔF) and (ΔP_{tie}). This work is first attempt to use steady state power flow analysis for the control of tie line power flow between two area power systems and there is no such work is available in literature.

2. RESEARCH METHOD

In the steady state power flow analysis, considering a system of N buses and assuming M numbers of voltage controlled buses. The unknowns are (N-M) number of voltage magnitudes at (N-M) buses and (N-1) number of voltage phase angles, at all buses except the reference bus. Considering the complex power balance equations at N buses, and separating the real and imaginary parts, 2N number of non-linear equations are obtained. This is solved by the application of De-coupled Newton-Raphson method as follows

$$S_i = P_i + j\,Q_i = V_i\, e^{j\delta I} \sum_{j=1}^{N} [\, Y_{ij}\, V_j\;\; e^{-j(\delta j + \theta ij)} \,] \quad (1)$$

$$P_i = (P_{gseti} + P_{gci}) - P_{Li} \quad (2)$$

$$P_{gset\,i} = -P_{gci} + P_{Li} + P_i$$

$$Q_i = Q_{gi} - Q_{Li}$$

$$Q_{gi} = Q_{Li} + Q_I \quad (3)$$

Assuming bus 1 as reference for the purpose of voltage phase angle calculations of other buses, the linearized equations for Decoupled Newton-Raphson iterative solution method can be written as:

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \ldots\ldots \\ \Delta P_N \end{bmatrix} = \begin{bmatrix} \partial P_1/\partial x & \partial P_1/\partial \delta_2 & \ldots\ldots & \partial P_1/\partial \delta_N \\ \partial P_2/\partial x & \partial P_2/\partial \delta_2 & \ldots\ldots & \partial P_2/\partial \delta_N \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots \\ \partial P_N/\partial x & \partial P_N/\partial \delta_2 & \ldots\ldots & \partial P_N/\partial \delta_N \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta \delta_2 \\ \ldots\ldots \\ \Delta \delta_N \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} \Delta Q_1 \\ \Delta Q_2 \\ \ldots\ldots \\ \Delta Q_{N-M} \end{bmatrix} = \begin{bmatrix} \partial Q_1/\partial V_1 & \partial Q_1/\partial V_2 & \ldots\ldots & \partial Q_1/\partial V_{N-M} \\ \partial Q_2/\partial V_1 & \partial Q_2/\partial V_2 & \ldots\ldots & \partial Q_2/\partial V_{N-M} \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots \\ \partial Q_{N-M}/\partial V_1 & \partial Q_{N-M}/\partial V_2 & \ldots\ldots & \partial Q_{N-M}/\partial \delta_{N-M} \end{bmatrix} \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \ldots\ldots \\ \Delta V_{N-M} \end{bmatrix} \quad (5)$$

The above relations can be written as $[\Delta P] = [J_1] \begin{bmatrix} \Delta x \\ \Delta \delta \end{bmatrix}$ (6)

$$[\Delta Q] = [J_2]\,[\Delta V] \quad (7)$$

Where ΔX is ΔF or ΔP_{tie}. Size of J_1 is [N, N] and J_2 is [(N-M), (N-M)]

Assuming initial bus voltages as 1 pu and X=0, the active and reactive powers are calculated from (6) and (7). The changes in powers are the differences between the specified and calculated values.i.e.

$\Delta P^K = P_{specified} - P_{calculated}$

$\Delta Q^K = Q_{specified} - Q_{calculated}$

The estimated bus voltages, X and calculated powers are used to evaluate the elements of the Jacobian matrices $J_1$and J_2. The linear set of (6) and (7) are solved for ΔX, $\Delta\delta$ and ΔV by the triangularisation method. In this paper, ΔX is considered as frequency deviation and tie line error. By varying the generation and load from minimum to maximum the range of frequency deviation ΔF and the tie line error (ΔP_{tie}) values are stored in a look up table. By varying the load from minimum to maximum the economic allocation of generation of each unit is stored in the look up table. The generator model, load model and algorithm used in this paper are given in [6].

2.1 Conventional Controller

The system frequency and tie-line power flow are acting as feed back signals for the controller. These signals are processed based on regulating characteristics (R_i), and participation factors of the generator units α_i of the power system to evaluate the required change in generation as given in eqn.

$\Delta P_{gi}=-(1/R_i)^* \Delta F_i + \alpha_i^* \Delta P_{tie.}$ Where, ΔF and ΔP_{tie} are the components of ACE.

The controller calculates the new generation schedule based on optimal generation and ACE Variation in load, requires change in each generating unit such that the new load be served in the most economic way. For stable operation, the governors are designed to permit the speed to drop as load is increased. The slope of the curve represents the speed regulation R which is 5%.

2.2 Generation Allocation with Generation Rate Constraints (GRC)

If each control area in an interconnected system had a single generating unit, the control system would suffice to provide stable frequency and tie-line exchange. However, power systems consist of control areas of many generating units with outputs that must be set according to economics. The total generation value will not usually exist for a very long time, since the load on the power system varies continuously. Therefore, it is impossible to simply specify a total generation. So, the economic dispatch of each unit is calculated, and then given to the control mechanism of each unit. The allocation of individual generator output over a total generation values is accomplished by using base points and participation factors. The base point and participation factors are used for calculation by the formula

$P_{ides} = P_{ibase} + \alpha_i \Delta P_{total}$ where, $\Delta P_{total}= P_{new\ total} - \sum P_{ibase}$

In power systems having steam plants, power generation can change only at a specified maximum rate. Normally the generation rate is between 5 to 10%/min. If these constraints are not considered, system is likely to chase large momentary disturbances. This results in undue wear and tear of the controller. Hence the maximum generation has to be fixed which is known as Generation Rate Constraint (GRC). In this work, the generation rate constraints are fixed at 5% of available generation ($\Delta P_{gi} \leq \Delta P_{gi\ max}$). If the ΔP_{gi} required by the systems is more than 5% of the current generation, ΔP_{gi} is equal to $\Delta P_{gi(max)}$. The excess generation required is achieved gradually. The GRC is considered in Fuzzy Logic Controller (FLC). It is added in output range of fuzzy set of the FLC.

2.3 Design of Fuzzy Logic Controller

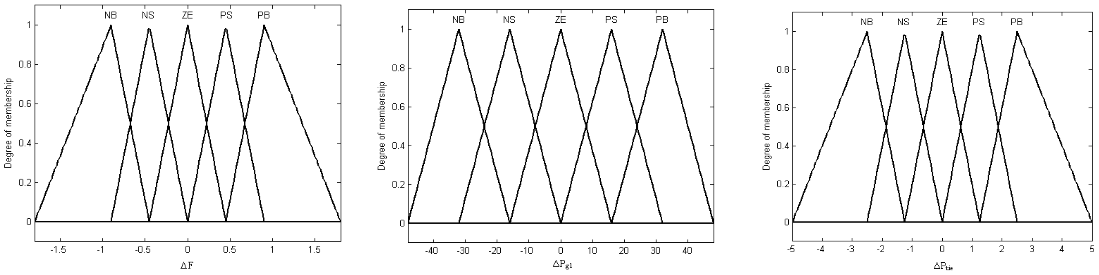
2.3.1. Identification of variables and Fuzzification

The ΔF and ΔP_{tie} are considered as input variables for the FLC. These are calculated by Decoupled Newton Raphson method. The output variable of the FLC is ΔP_{gi}. Fuzzification is the process of making crisp value into fuzzy quantity. A fuzzification performs the function that converts crisp ΔF and ΔP_{tie} into fuzzy sets.

2.3.2. Determination of membership function

The range of input variables (ΔF and ΔP_{tie}) and output variables lies within a range, which is designed based on conventional controller results. The ranges of input and output variables are then assigned with linguistic variables to transform the numerical values into fuzzy quantities. The input and output variables are assigned with five linguistic variables named as Negative Big [NB], Negative Small [NS], Zero [ZE], Positive Small [PS] and Positive Big [PB]. Among all membership function, triangular membership function is implement as in Fig. 1. The triangular membership function with {Δ F (real values), a (minimum), b (medium), c (maximum)} is defined as:

$$\mu F = \begin{cases} 0 & \Delta F \in a \\ (\Delta F - a)/(b-a) & \Delta F \in (a,b) \\ (c-\Delta F)/(c-b) & \Delta F \in (b,c) \\ 0 & \Delta F \geq c \end{cases}$$



a. Membership Function for ΔF b. Membership functions for ΔP_{tie} c. Membership functions for ΔP_{g1}

Fig. 1 Membership functions

2.3.3 Formulation of rule base

The input and output conditions described by fuzzy sets are given as

R^i: if ΔP_{tie} is I_1^r and ΔF is I_2^r, then ΔP_{gi} is O^r Where, I_1, I_2 correspond to input linguistic variables, O corresponds to output linguistic variable and i indicates i^{th} fuzzy logic rule. For example, ΔF and ΔP_{tie} are Negative Big (NB) indicates the available generation is less in that area. To compensate that, the generation has to be increased by $\Delta P_{gi,}$ hence PB should be the linguistic output. The other rules are framed and given in Table 1.The range of ΔF and ΔP_{tie} are given in Table 2

Table 1. Rule Base Matrix

ΔP_{tie} / ΔF	NB	NS	ZE	PS	PB
NB	PB	PB	PB	PS	ZE
NS	PB	PS	PS	ZE	NS
ZE	PB	PS	ZE	NS	NB
PS	PS	ZE	NS	NS	NS
PB	ZE	NS	NB	NS	NB

Table 2. Membership Function Ranges

	ΔF			ΔPtie		
NB	-2	-1.333	-0.666	-5	-3.333	-1.666
NS	-1.333	-0.666	0	-3.333	-1.666	0
ZE	-0.666	0	0.6666	-1.666	0	-1.666
PS	0	0.6666	-1.333	0	1.666	3.333
PB	0.6666	1.3333	2	1.6666	3.333	5

The shaded regions in Table 1 show conditions which are practically impossible. For example when ΔF is PB it means that available generation is excess than the load. For this case ΔPtie cannot be NB or NS as this would indicate that the available generation is less than the load which is contradictory to the above statement. Hence this case is not possible.

2.3.4 Defuzzification

Tthe membership functions μ_B' of the output linguistic variable 'B' is singly defuzzified for each rule such that each function is reduced to a singleton. It should be noted that for various rules (r =1…R) would be in operation for a set of (ΔF, ΔP_{tie}), each recommending possibly different fuzzy controller actions as in [6]. The defuzzified output is obtained by the following expression

$$u = \frac{\sum_{r=1}^{R} \mu_r' H_r}{\sum_{r=1}^{R} H_r}$$

Where μ_r' is the membership value of the linguistic variable recommending the fuzzy controller action and H_r is the precise numerical value corresponding to that FLCaction.

3. RESULTS AND ANALYSIS

In this work, the power system considered includes two areas connected through tie-lines. The effects of generating rate boundaries are also included in these areas. The proposed model is controlled by conventional controller and FLC. To test the model, the load is increased and decreased in some of nodes.

3.1 IEEE 30 Bus System

Modified IEEE 30 bus system is used for simulation study which is shown in Fig 2. The IEEE 30 bus system is divided into two areas, Area1 and Area2 as given in the paper [12]. There are six interconnected lines between Area1 and Area2. In this project, the line between the buses 27-28 is considered as tie line and the other five lines between buses 6-10, 9-10, 10-17, 10-20 and 23-24 are removed from the circuit to perform the tie line power flow analysis as shown in Fig 3 .

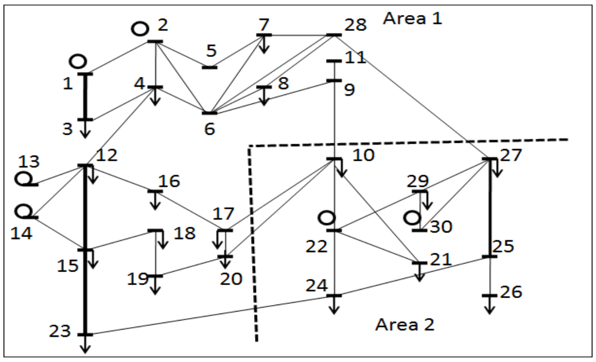


Fig 2. IEEE 30 Bus System

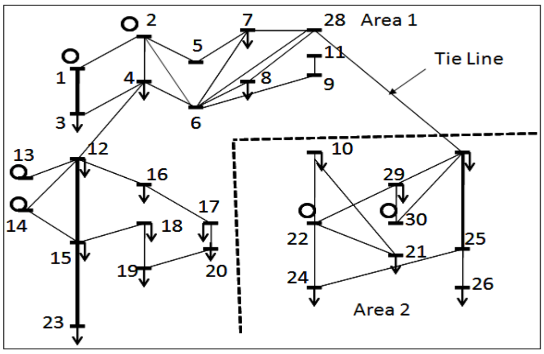


Fig 3. Modified IEEE 30 Bus System

3.2 Base Case

The controllers are implemented in IEEE 30 bus system with 6 generating units. The economic generation schedule and the load on the system at steady state, before the application of any change in generation or load (mentioned as base case) are given in Table 3. The value of tie line error (ΔPtie) lies between ± 2%. For all cases generation rate constraint is chosen as 5%. The lower limit for frequency deviation (ΔF) is kept as 0.005 Hz and for tie line error is 0.5 MW. Hence the precision obtained is 0.01% for ΔF and 0 .1% for ΔPtie.

Table 3. Base Case

Pg1 in MW	Pg2 in MW	Pg3 in MW	Pg4 in MW	Pg5 in MW	Pg6 in MW	Total Generation in MW	Total Load in MW	Total Loss in MW
48.0549	24.0275	12.0137	88.4248	21.5677	51.0218	245.5601	222.8	22.7601

3.3 Power flow in Two Area

The load on bus 26 is increased from 0 MW to 16 MW. Then it is gradually incremented by 2 MW. The real power flow and reactive power flow in line is increased from -1.789 MW to -2.447 MW. The tie line flow limit is chosen as 10 MW. The analysis is carried out for both Conventional and Fuzzy Logic Controller. When the load reaches 20 MW, the maximum limit on line flow is reached and beyond this point even if the load is increased, the generation as well as the tie line flow does not increase to compensate for the increase in load. From the Fig 4 and Fig 5, it is observed that with increase in the load, ACE increases and to compensate for this increase, generation of each generation bus increases. The tie line flow also increases with increases in load. It can also be observed that for FLC the increase in generation with load is more uniform compared to conventional controller.

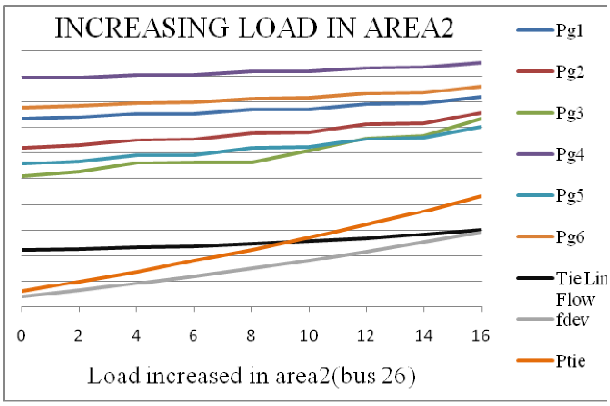


Fig. 4 Increasing Load in Area2 for Conventional Controller

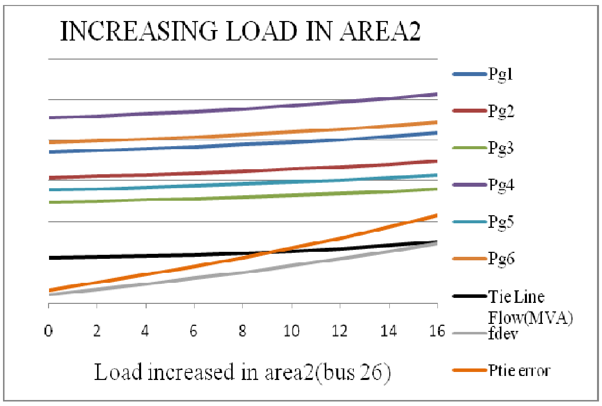


Fig. 5 Increasing Load in Area2 for FLC

3.4 Load Perturbations

For comparing the performance of Conventional and Fuzzy Logic Controller following cases are considered. The Load is increased and decreased in both areas one by one. The results are tabulated. Then graph is plotted between error and number of iterations.

3.4.1 Increase in load in Area 1 and Area 2

For comparing the performance of Fuzzy Logic Controller and Conventional Controller load is increased in Area 1, the load is increased by 60 MW. The generation schedule, loss, cost, number of iterations and minimum value ACE are given in Table 4. The load is increased in Area 2 by 60 MW. The results are tabulated in Table 5.

Table 4. Increase in Load in Area 1

Generation Schedule in MW	Conventional Controller	Fuzzy Logic Controller
Pg1	59.777	61.2388
Pg2	35.3312	30.6199
Pg3	23.3174	15.309
Pg4	100.5659	112.6839
Pg5	33.2901	27.4855
Pg6	62.3255	65.0196
Total Generation in MW	314.6071	312.3570
Total losses in MW	23.9145	21.6481
Cost in $/h	1844.4	1831.1
No of iterations	59	38
Minimum ACE obtained	0.0048	0.0047

Table 5. Increase in Load in Area 2

Generation Schedule in MW	Conventional Controller	Fuzzy Logic Controller
Pg1	37.0168	36.8479
Pg2	13.4025	18.4235
Pg3	10.1187	10.0000
Pg4	76.9736	67.8033
Pg5	10.5296	16.5373
Pg6	40.3968	39.1229
Total Generation in MW	188.4350	188.7348
Total Losses in MW	15.2670	14.7123
Cost in $/h	1330.24	1315.9
No of Iterations	74	62
Minimum ACE obtained	0.0047	0.0046

3.4.2 Decrease in load in Area 1 and Area 2

Similarly the load is decreased in Area 1 by 50 MW. And the performance of Fuzzy Logic Controller is compared with Conventional Controller. The generation schedule, loss, cost, number of iterations, minimum error are tabulated in Table 6. Load is decreased in Area 2 by 50 MW. Results are tabulated in Table 7.

Table 6. Load Decrease in Area 1

Generation Schedule in MW	Conventional Controller	Fuzzy Logic Controller
Pg1	37.0404	37.2888
Pg2	13.4317	18.6439
Pg3	10.3335	10.0000
Pg4	76.9915	68.6145
Pg5	10.5532	10.7350
Pg6	40.4260	39.5910
Total Generation in MW	188.7762	190.8732
Total Losses in mW	18.9081	19.2893
Cost in $/h	1331.19	1324.6
No of iterations	72	61
Minimum ACE obtained	0.0047	0.0046

Table 7. Load Decrease in Area 1

Generation Schedule in MW	Conventional Controller	Fuzzy Logic Controller
Pg1	37.0168	36.8479
Pg2	13.4025	18.4235
Pg3	10.1187	10.0000
Pg4	76.9736	67.8033
Pg5	10.5296	16.5373
Pg6	40.3968	39.1229
Total Generation in MW	188.4350	188.7348
Total Losses in MW	15.2670	14.7123
Cost in $/h	1330.24	1315.9
No of Iterations	74	62
Minimum ACE obtained	0.0047	0.0046

4. CONCLUSION

In this paper, the fuzzy based power flow control of two area power system is experimented using steady state power flow analysis by decoupled Newton Raphson method. The control action is performed by conventional method using participation factor and Fuzzy Logic Controller (FLC). The method is tested with modified IEEE 30 bus system. The FLC is designed for scheduling the generation to minimize ACE as well as tie line error between two areas. The output of FLC is compared with Conventional controller in terms of generation schedule, tie line error, cost and iterations. The results show that tie line power flow control using FLC is better than conventional controller in many aspects.

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