Load Frequency Control of a Nonlinear Two-Area Power System

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***Abstract*— In an interconnected power system, all the generators must run at an appropriate capacity to meet the demand in power. Loss of synchronism between the generators and/or too much frequency fluctuations may cause protective equipment to trip. Load frequency control (LFC) is necessary to balance the power generation and the load, by monitoring frequency and power changes between interconnected power systems in tie-lines. In this paper, power systems from previous research works are analysed for stability, and different types of controllers are designed and validated through simulation and compared with a Proportional-Integral-Derivative (PID) - controlled power system. Three types of controllers are considered, namely Fuzzy, Fuzzy-PID and Adaptive Neuro-Fuzzy controllers. The first power system considered is a linear identical non-reheat two-area system. However, a linear system does not model an actual power system completely because of neglected nonlinearities. Hence, two main sources of nonlinearity (generation rate constraint (GRC) and governor dead band (GDB)), which arise due to practical constraints are considered and included in the model of the system.**

Keywords*— Load Frequency Control, Fuzzy, Adaptive Neuro Fuzzy, Fuzzy-PID, Governor Deadband, Generation Rate Constraint.

I. INTRODUCTION

An electrical power service aims at providing reliable and uninterrupted electricity. Reliable and uninterrupted mean that the supply must be of constant RMS voltage and frequency. In real life, of course this is not possible and hence a tolerance range according to the service provider is used. This range must be within a certain norms. For example, if there is a voltage drop of 10-15% or a frequency drop of a few hertz, there is a risk of stalling in motor loads but usually, generators trip on voltage or frequency before this happens. An electrical grid involves a lot of planning and simulation and its operation is complex. Hence, automatic control is used in the system instead of human control because fast reaction speed is needed.

In an electrical grid, many synchronous generators with different voltage ratings are connected to bus terminals which have the same frequency and phase sequence as the generators. All generators connected in parallel must be run at the appropriate capacity to meet the demand. If a generator loses synchronism, there will be fluctuations in the voltage and frequency supply. It is essential to synchronise the bus with the generators throughout transmission for stable operation. This is called power system stability.

Power system stability, also known as synchronous stability refers to the ability of a system to return to synchronism after any disturbance such as a sudden change in loading conditions. Supply frequency and voltage must always be within a certain limit to ensure safe and reliable operation of electrical equipment and apparatus both at the consumer premises and during transmission and distribution. Thus it is essential to be able to monitor and keep the voltage and frequency within limits.

After a perturbation involving a net change in power, the system will enter a transient state which is normally oscillatory and reflected by fluctuations in the power flow over transmission lines. This is called the dynamic system performance. In a tie-line connecting one group of generators to another, these oscillations may build up and be reflected by excessive fluctuations in power flow in the tie line. This will cause protective equipment to trip [1].

A stable system is one in which after any perturbation, the synchronous machines remain in synchronism at the end of a finite transient period. Moreover, the amplitude of the oscillations in the transient period must be kept within a control. Besides, if there is any prolonged change, as long as these changes are within a predefined limit, the system must remain stable and both frequency and voltage kept constant.

To accomplish LFC, a controller is used to make the system return to synchronism after any load change. As input, the controller needs the error signal which is the difference between the desired and the actual output value. The controller will then generate a control signal which will affect the system's output value by amplifying it or attenuating it in an attempt to obtain the desired output. Controllers can be adjusted to improve transient response by decreasing maximum overshoot and settling time and also to improve steady state response by removing steady state error.

Electrical energy is one of the most important resources and hence optimization in power systems is essential. LFC is thus important and being able to design optimal but cheap controllers is of upmost priority. There is a wide variety of controllers designed using different methods, each offering distinct advantages and disadvantages. There are conventional controllers like PID and other interesting concepts like fuzzy controllers. It is useful to compare the actual impact of these controllers on a system and subsequently move towards optimal control.

The aim of this paper is to design a controller to perform LFC. At first an analysis of different systems from previous research works was performed. The Matlab/Simulink platform was used for all simulation results obtained. The stability of the systems was investigated and the transient and steady state response of the systems were simulated before any controller was designed.

The control objective is to reduce overshoot, settling time and steady state error. In LFC, deviation in frequency and tie line power should return to zero in the minimum time and with minimum overshoot after a load change [2]. Controllers were designed and tested to achieve this. Different types of controllers were simulated in Simulink for the system namely the PID, Fuzzy, Neuro-Fuzzy and Fuzzy-PID to improve its performance. Finally a comparative analysis of the results from the different controllers was done and the most appropriate one was chosen.

A. *Fuzzy Controller*

The design of a fuzzy controller involves three main processes:

1. Fuzzification which requires mapping input data to fuzzy sets.
2. Inference process which describes the decision making block. In this process, fuzzy inputs are mapped on corresponding fuzzy outputs based on their membership.
3. Defuzzification, a process where the fuzzy output from the inference process is converted to a non-fuzzy output which will then be the controller output [3], [4].

The fuzzy logic approach is similar to the decision making process of a human operator who uses his experience to process information and take appropriate measures.

1) *Fuzzy logic and Membership functions*

A fuzzy controller uses fuzzy logic. In a classical set theory, an individual is either a member or not a member of the set. In fuzzy logic, an individual can be in a set partially and partially in another set. This is illustrated in Figure 1.

In fuzzy sets, members have a partial membership values which show the degree to which they belong to each set. The fuzzy sets are described by membership functions which gives the membership, in the form of a continuous value between 0 and 1, of any individual. The membership function can be anything but most common ones are the triangular function shown in Figure 2 and the Gaussian membership functions [5].

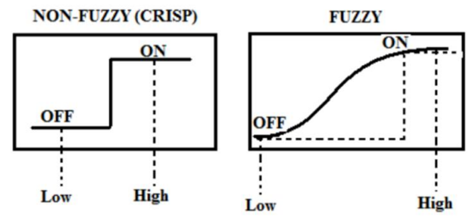

Figure 1 Fuzzy Numbers [4]

The input to a fuzzy controller is usually a crisp value. In the process of fuzzification, the membership functions are used to map the crisp values onto the corresponding fuzzy values with associated partial memberships [6]. Each fuzzy set can be described by linguistic variables such as ‘very fast’ or ‘slow’. These linguistic variables can then be used in the construction of fuzzy rules.

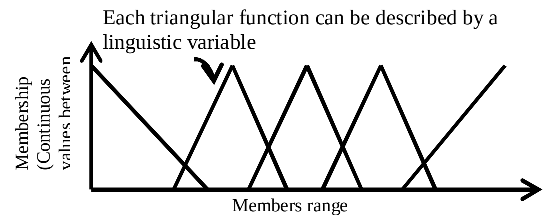

Figure 2. Membership Functions

The advantage of fuzzy logic is that it tries to imitate human reasoning by even using linguistic variable and is hence easier to understand for the designer [7], [8]. Fuzzy logic also allows for uncertainty, approximations and vague, incomplete and inconsistent description of a member, it is often more suitable for practical problems than conventional methods. Most data cannot be classified to be completely in one set without any connection to another set.

2) *Fuzzy Rules Construction*

The fuzzy rules in the controller describe how the controller should react under each combination of inputs [9]. Operations in fuzzy logic rules are AND, OR, NOT, implication and equivalence.

Using the linguistic variables, fuzzy rules can then be constructed. The general form of the fuzzy rules is the ‘IF-THEN’ rule. The inference process makes use of the rules to make decisions. For example, ‘IF Very fast AND Raining THEN low output’ where inputs ‘Very fast’ and ‘Raining’ and output ‘low output’ are linguistic variables.

3) *Defuzzification*

The output of the fuzzy controller will be in the form of fuzzy linguistic variables. The defuzzification process converts these fuzzy outputs into crisp outputs. It combines all the possible control outputs into an average formula and creates a crisp overall control signal.

The defuzzification method used in this dissertation for Mamdani FIS is the center-of-gravity (centroid formula) given by:

$$u(t) = \frac{\int \mu_i(x).x\,dx}{\int \mu_i(x)dx} \quad (1)$$

where,
$\mu_i(u)$ is the aggregated membership function,
x is the output variable
There are many other methods of defuzzification [5], [10].

A. *PID Controller*

A proportional integral derivative (PID) controller involves three parameters, the proportional, integral and derivative gain.
Often not all three control actions are needed to optimally control a system with minimal cost and hence P, I, PI and PD controllers can also be used. PID controllers are very popular in the industrial field because of their simplicity and low cost while effectively improving transient and steady state responses even when the actual working principles and parameters of the system are unknown.

B. *Fuzzy PID Controller*

The Fuzzy-PID controller uses a fuzzy and a PID controller together to improve the control action. The membership functions and fuzzy rules are difficult to fine tune to obtain the best response. Besides, both fuzzy and PID controllers are not adaptive, meaning that if the set-point is changed, the system may not be optimally controlled anymore or even become unstable. Using a fuzzy and a PID as cascaded controllers such that the fuzzy controller adjusts the parameters of the PID controllers depending on the actual response of the system results in an online and more optimal control.

C. *Neuro-fuzzy Controller*

In Neuro-fuzzy controllers, a set of training data representing the desired response of the controller is used to train the fuzzy controller's rules and membership functions. This is done using the Adaptive Neuro-Fuzzy Inference system, ANFIS function in Matlab/Simulink.
For this type of controller, the ANFIS training routine trains a Sugeno-type fuzzy inference system using hybrid training algorithm (a combination of backpropagation gradient descent method and least-squares method) to identify the parameters of the FIS.

II. METHODOLOGY

A linear two-area system and a nonlinear two-area system considered for LFC. All systems are analysed to observe their initial response.
After this various types of controllers are designed for the two-area systems such as PID, Fuzzy, Fuzzy-PID and adaptive Neuro-Fuzzy so that a comparative analysis can be later performed. The systems are implemented in the form of block diagrams in the s-domain and simulated. Controllers are designed using the control system toolbox which can be used to tune predefined controllers such as PID and Fuzzy so as to adapt them to a particular system.

A. *Systems*

The stability of the system is checked by analysing the uncontrolled system's response to confirm if the frequency deviation and incremental tie line power responses tend to finite values.

1) *Linear Two Area System*

The two-area interconnected power system proposed by [11] is used with a load change of 0.01 pu MW for area 1 and 0.02 pu MW for area 2. The areas are both large systems of 1000MW, 60Hz each [14].

2) *Non-Linear Two Area System*

Considering an uncontrolled non-linear system [12],[13], a Generation Rate Constraint (GRC) of 10% pu MW min^{-1} (0.0017 % pu MW s^{-1}) and a Governor Deadband (GBD) of 0.05 % were added to the linear two area system for each area [15], [16].

B. *Fuzzy Controller*

A fuzzy controller is now designed for each area of the two-area system. Matlab/Simulink inbuilt fuzzy block is used. To create the FIS which defines all the parameters of the fuzzy block, 'fuzzy' is typed in the Matlab command window so as to open the FIS editor. Before starting the simulation, the FIS are exported to the workspace and the name of the corresponding FIS is used as parameter for the fuzzy block.

$$ACE_i = B_i\Delta f_i + \Delta P_{tie,I} \quad (2)$$

where,
ACE_i is the Area Control Error,
i is the Area number,
Δf_i is the frequency deviation,
B_i is the frequency bias parameter [17-19]
The variables being controlled are ACE and $\dot{ACE}$ input variable and there will be one output variable, the control action. The area control error is often used as the controller input.
By using ACE as our controller input, deviations in both Δf and ΔP_{tie} can be reduced.
Next the membership functions are defined using the Fuzzy Inference System (FIS) membership function. Seven Triangular membership functions are used for both the input and control variables. The ranges of the membership functions are initially set according to the ranges of the chosen input variables in the uncontrolled two-area system. Afterwards, the linguistic variables are assigned.
The defuzzification method is taken as centroid. The rules are designed approximately by logic and then fine-tuned by trial

and error to obtain the best control action. The weight of each rule is kept at 1. The ranges of the membership functions are adapted to obtain a better control action and the rules are tuned again to improve response.

C. Fuzzy-PID Controller

The same method as in fuzzy controllers is used to design the fuzzy rules and set the fuzzy membership functions. The output of the fuzzy controller is connected to a PID controller.

D. Adaptive Neuro-Fuzzy Controller

The same system as for the Fuzzy controlled system is used except that the FIS is a Sugeno-type designed using the Adaptive Neuro Fuzzy Inference System (ANFIS) editor.
The AND method is set as product and weighted average is used for defuzzification.
A set of training data representing the inputs and desired controller output is obtained from the two-area system with a PID controller. The training data set is loaded in the ANFIS editor and an initial FIS is generated using grid partition. The number of membership functions for the inputs is set to 7 and the output is set to be linear. The FIS is then trained for 10 epochs using the hybrid optimization method and tolerance 0.

III. DATA ANALYSIS AND FINDINGS

The systems were first analysed for a step load change of 0.01 pu MW for the first area and 0.02 pu MW for the second area. The same step changes was initially used for the different controllers to be able to compare their performances. Then, different load changes were applied to the controlled systems to investigate their responses under different conditions.

A. Uncontrolled two area system

As can be observed from Table I, even though the same step load changes are applied in all systems, there are discrepancies when nonlinearities are added to the system.
When GRC is added, the steady state error, the settling time and the maximum overshoot increases for Δf and ΔP_{tie} in both areas. This is because GRC limits the rate of change of power generation. When both GDB and GRC are present, settling time increases by a much greater amount due to the very oscillatory response of system.
On the other hand, steady state error and maximum overshoot decrease slightly compared to system with GRC only. This is because GDB adds a range of inputs in the system for which there is no reaction.

B. Controlled Linear Two Area System

It can be observed from Table III, that in terms of settling time, adaptive Neuro-fuzzy controller perform best with a decrease in settling time of over 40% for all responses. It also has good performance in terms of maximum overshoot reduction which is above 70%. However it has the poorest performance in terms of steady state error. The PID controller gave zero steady state error and greatly decreased maximum overshoot by above 80% in all areas but had poor performance in terms of settling time (reduction of 0.082% to 11.41%) compared to other controllers.
On the other hand, the fuzzy controller provided good performance in terms of settling time (above 30%) but little reduction of maximum overshoot (around 40% for frequency deviation in both areas) and steady state error was still present.

The Fuzzy-PID controller designed completely removed steady state error and gave more than 80% reduction in maximum overshoot for all responses. Besides, though not the best, it gave good enough reduction in settling time of more than 25% for both Δf and ΔP_{tie}.. Different load changes are then applied to the Fuzzy-PID system to check if it can perform well in different conditions.
As can be observed in Figure 3, the Fuzzy-PID system performs well for other load changes including negative load changes.

C. Controlled Non-Linear Two Area System

As can be observed in Table IV, steady state error could not be completely removed though reduced to very small amount.
This is because of the oscillatory nature of the system when GDB was added. In terms of settling time, both types of controllers offered similar improvement. However, the Fuzzy-PID controller gave better response in terms of maximum overshoot.
The controlled system is now tested under different load changes. As can be seen from Figure 4, the system responds well even with other load changes.

Table I Uncontrolled Two Area System

	Linear two-area system				**Two-area system with GRC**				**Two-area system with GRC and GDB**			
	Area 1		Area 2		Area 1		Area 2		Area 1		Area 2	
	Δf/Hz	ΔP_{tie}/pu MW	Δf/Hz	ΔP_{tie}/pu MW	Δf/Hz	ΔP_{tie}/pu MW	Δf/Hz	ΔP_{tie}/pu MW	Δf/Hz	ΔP_{tie}/pu MW	Δf/Hz	ΔP_{tie}/pu MW
Steady state value	-0.035	0.005	-0.035	-0.005	-0.327	0.005	-0.327	-0.005	-0.292	0.004	-0.292	-0.004
Maximum Overshoot	0.044	0.006	0.052	0.006	0.331	0.010	0.330	0.010	0.365	0.010	0.368	0.010
Settling time/s	5.55	6.13	5.44	6.13	9.87	17.3	8.95	17.3	68.3	154.7	67.1	154.7

Table II Controller Types

Controller number	Controller type
1	PID
2	Fuzzy with Δf and ΔP_{tie} as inputs
3	Fuzzy with ACE and $\dot{ACE}$ as inputs
4	Fuzzy-PID
5	Adaptive Neuro-Fuzzy

Table III Controlled Linear Two Area System

			Change in maximum overshoot/ %	Change in settling time%	Change in steady state error/%
Δf	Area 1	1	-90	-0.082	-100
		2	-72.27	-3.52	-99.7
		3	-39.55	-45.98	-99.4
		4	-90.45	-26.62	-100
		5	-72.05	-59.52	-66.86
	Area 2	1	-84.2	-11.1	-100
		2	-82.86	15.69	-99.7
		3	-39.43	-43.42	-99.43
		4	-82.48	-33.86	-100
		5	-76.57	-62.53	-66.86
ΔP_{tie}		1	-93.3	-11.41	-100
		2	-11.86	-21.06	0
		3	-89.77	-30.08	-98.39
		4	-90.55	-32.39	-100
		5	-96.37	-41.54	-97.94

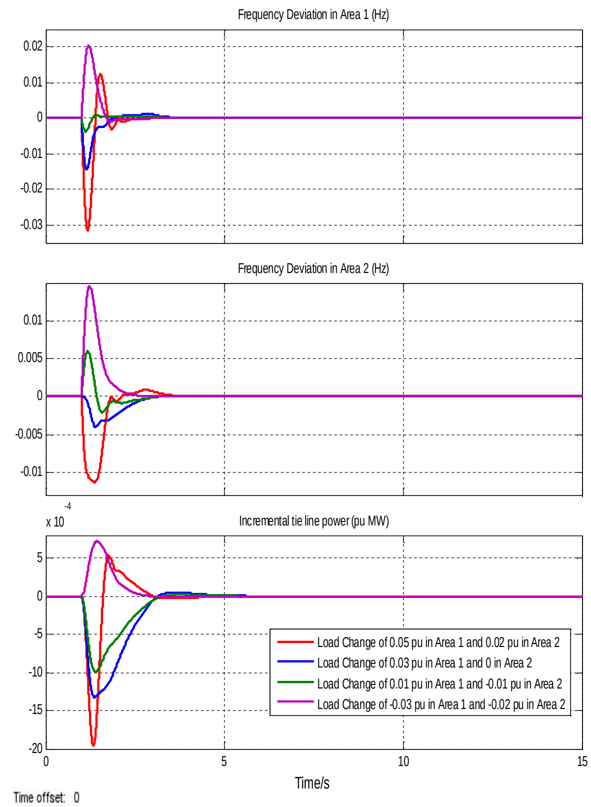

Figure 3. Linear two area system with Fuzzy-PID controller response under different load changes

Table IV Controlled Non-Linear Two Area

			Δ maximum overshoot/%	Δ settling time%	Δ steady state error /%
Δf	Area 1	PID	-15.14	-62.96	-99.86
		Fuzzy-PID	-25.99	-65.13	-99.82
	Area 2	PID	-16.73	-62.42	-99.96
		Fuzzy-PID	-26.8	-64.86	-99.78
ΔP_{tie}		PID	3.33	-83.36	-98.67
		Fuzzy-PID	2.08	-82.24	-99.23

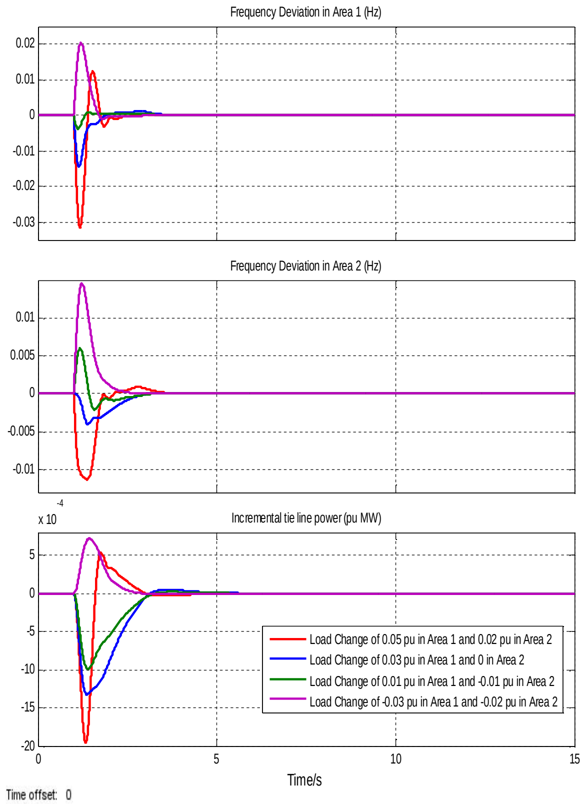

Figure 3. Linear two area system with Fuzzy-PID controller response under different load changes

IV. CONCLUSION

From simulation results obtained, it can be concluded for the linear two area system, the Fuzzy-PID controller offered the best overall performance with elimination of steady state error, more than 80% reduction of maximum overshoot and over 25% reduction in settling time. Also, it was found that by adding GRC and GDB as non-linearities to the system leads to larger settling times, higher maximum overshoot and steady state errors. Moreover, upon designing controllers for the non-linear two area system, the Fuzzy-PID controller only gave slightly better performance than the anti-windup controller.

Hence, it can be concluded that Fuzzy-PID controllers should be considered and following the trend of mostly using PID controllers in industrial environment may not always lead to the best control action. However, it was also observed that there is not a single controller which will give the best control action in all situations. Instead, each controller gives different performances when applied to the different systems under consideration.

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