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A Novel Methodology of Fuzzy Logic Controller for A Dynamically Interconnected Electric Power System

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Abstract: *This paper presents a novel methodology for designing a fuzzy controller for a dynamically interconnected electric power system. One controller with constant gains for different operating points may not be sufficient to guarantee satisfactory performance for Load Frequency Control. Therefore, the knowledge-based fuzzy controller is proposed either to cope with the operating conditions or to remove any fixed mode. The fuzzy logic control utilizes the error and the change of error as fuzzy linguistic inputs to regulate the system performance. The proposed control scheme is applied to a two-area power system provided with both hydraulic and thermal turbines.*

Keywords: *Fuzzy Logic Control "FLC", Load Frequency Control "LFC". Interconnected Power System "IPS"*

I. Introduction

Load Frequency Control "LFC" is a very important factor in power system operation. It aims at controlling the output power of each generator to minimize the transient errors in the frequency and tie-line power deviations and to ensure its zero steady state errors [1-6].

Load Frequency due to the variation of the operating condition, one controller with constant gains may not be sufficient to guarantee satisfactory performance for the overall system.

Emergence of a new advanced technology is intimately dependent on the connection between artificial intelligence and human thought. This in turn, would require computers to understand human's language.

This paper presents a fuzzy logic controller to provide robust control characteristics. In general, the human knowledge of the system control is based on the expertise, intuition, knowledge of the system's physical behavior, or a set of subjective goals.

This type of knowledge is usually expressed in the form of linguistic rules. In regard, a fuzzy logic controller is a knowledge-based controller that makes use of fuzzy set theory [7-10].

This paper is organized as follows, the second section describes the power system control problem,. The third section is devoted to discuss the fuzzy control scheme. The fourth section is concerned with the design of the proposed fuzzy control scheme. Finally the last section is concerned with the analysis of simulation results.

II. Modeling Of LFC

Load Frequency Control "LFC" sometimes, called Automatic Generation Control "AGC" is a very important aspect in power system operation and control for supplying sufficient and reliable electric power with the desired quality [6].

Load Frequency Control generally involves several designed power areas within an integrated power grids with each area responsible for controlling its Area Control Error "ACE".

We can therefore state that the Load Frequency Control (LFC) has the following two objectives:

- Hold the frequency constant ($\Delta f = 0$) against any load change. Each area must contribute to absorb any load change such that frequency does not deviate.
- Each area must maintain the tie-line power flow to its pre-specified value.

Power deficits may be pure active, pure reactive, or combined. Any of these deficits affects the frequency of the system directly.

2.1-Power Generating Units

2.1.1-Turbines

A turbine unit in power systems is used to transform the natural energy, such as the energy from steam or water, into mechanical power ($\Delta Pm = \Delta Pg$) that is supplied to the generator.

The transfer function can be of the non-reheat turbine is represented as

$G_{TT}(s) = \Delta P_g / \Delta Xg= 1 / (1+ST_T)$ **(1)**

where $\Delta X_g=\Delta P_v$ is the valve/gate position change for steam turbine, and T_T is the turbine time constant

Hydraulic turbines are non-minimum phase units due to the water inertia. In the hydraulic turbine, the water pressure response is opposite to the gate position change at first and recovers after the transient response. Thus the transfer function of the hydraulic turbine is in the form of

$G_{THd}(s) = \Delta P_g /\Delta H_g= (1- T_w) / (1+0.5ST_w)$ **(2)**

where ΔH_g is the valve/gate position change for hydraulic turbine, and Tw is the water starting time

2.1.2- Generators

A generator unit in power systems converts the mechanical power received from the turbine into electrical power. But for LFC, we focus on the rotor speed output (frequency of the power systems) of the generator instead of the energy transformation. Since electrical power is hard to store in large amounts, the balance has to be maintained between the generated power and the load demand

Once a load change occurs, the mechanical power sent from the turbine will no longer match the electrical power generated by the generator. This error between the mechanical (ΔPm) and electrical powers (ΔPel) is integrated into the rotor speed deviation ($\Delta\omega_r$), which can be turned into the frequency bias (Δf) by multiplying by 2π.

The relationship between ΔPm and Δf is shown in Fig.1, where M is the inertia constant of the generator. The power loads can be decomposed into resistive loads (ΔPL), which remain constant when the rotor speed is changing, and motor loads that change with load speed . If the mechanical power remains unchanged, the motor loads will compensate the load change at a rotor speed that is different from a scheduled value, where D is the load damping constant.

$\Delta Pm(s) - \Delta PL(s) =(Ms+D)\Delta F(s)$ **(3)**

The reduced system is shown in Fig.1,

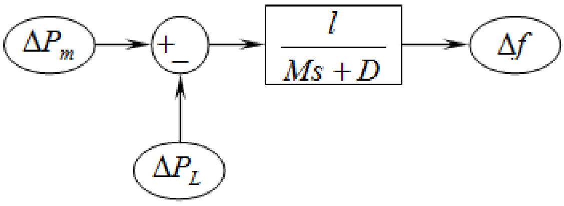

Fig. 1 Reduced block diagram of the generator with the load damping effect.

2.1.3- Governors

Governors are the units that are used in power systems to sense the frequency bias caused by the load change and cancel it by varying the inputs of the turbines. The schematic diagram of a speed governing unit is shown in Fig. 2, where R is the speed regulation characteristic and Tg is the time constant of the governor.

If without load reference, when the load change occurs, part of the change will be compensated by the valve/gate adjustment while the rest of the change is represented in the form of frequency deviation.

The goal of LFC is to regulate frequency deviation in the presence of varying active power load. Thus, the load reference set point "U=ΔPc" can be used to adjust the valve/gate positions so that all the load change is canceled by the power generation rather than resulting in a frequency deviation. The transfer function of the governor-thermal “GT” system is described by:

$U-\Delta F(s) / R=(1+ST_g) \Delta X_G$ **(4)**

Where U "ΔPc" is the incremental change in the speed changer position of the governor system and $\Delta X_g=\Delta P_v$ is the valve/gate position change for steam turbine.

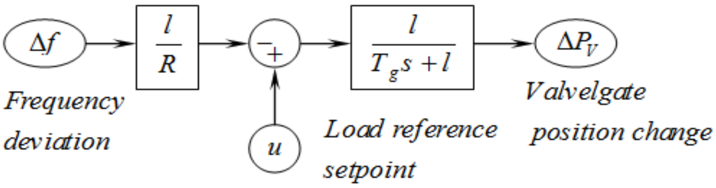

Fig.2: Reduced block diagram of the speed governing unit

2.1.4-Tie-Lines

In an interconnected power system, different areas are connected with each other via tie-lines. When the frequencies in two areas are different, a power exchange occurs through the tie-line that connected the two areas. The tie-line connections can be modeled as shown in Fig. 3.

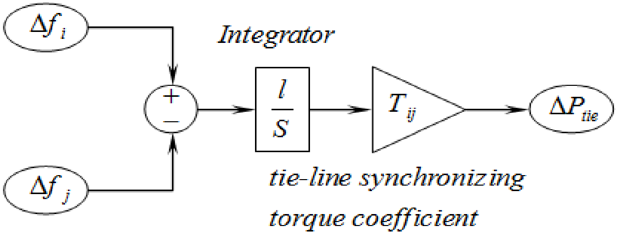

Fig.3 : Block diagram of the tie-lines.

where $\Delta P_{tiei\text{-}j}$ is tie-line exchange power between areas i and j, and Tij is the tie-line synchronizing torque coefficient between area i and j.

III. Two-Area LFC System

Let us consider a two-area connected by a single tie-line. Fig. 4 shows the functional block diagram of the Two Mixed Area Interconnected Power System (TMAIPS).

The control objective of the two area with tie-line connection is now to regulate the frequency of each area and to simultaneously regulate the tie-line power as per inter-area power contracts.

Each control area can be represented by an equivalent turbine, generator and governor system. The converter is used to convert the frequency deviation into a valve/gate position of governor.

Symbols with suffix 1 refer to Area 1 and those with suffix 2 refer to Area 2. Control Area 2 Control Area 1 Tie Line 1 2.

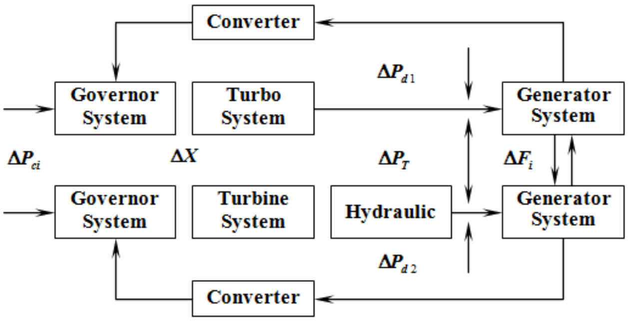

Fig.4 Functional Block diagram of Hydro-Thermal Interconnected power system.

The transfer functions of the Two Mixed Area Interconnected Power System (TMAIPS) are shown in Fig.5. The problem of the LFC of an IPS can be expressed mathematically as follows [6]. Where X is the state vector, and U is the control vector.

$$\mathbf{X} = [X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8]$$

$$= [\Delta F_1, \Delta X_{g1}, \Delta P_{g1}, \Delta F_2, \Delta X_{g2}, \Delta H_{g2}, \Delta P_{g2}, \Delta P_{tie1,2}] \quad (5)$$

$$\mathbf{U} = [U_1, U_2, U_3, [U_4]$$

$$= [\Delta P_{c1}, \Delta P_{d1}, \Delta P_{c2}, \Delta P_{d2}] \quad (6)$$

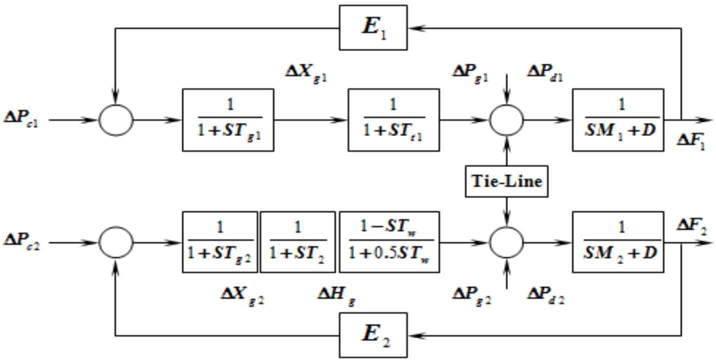

Fig.5 Transfer Function of Hydro-Thermal Interconnected power system.

The interlinking of the various areas in case of a two-area system is through the tie-line power exchange. The commitment is the tie-line power interchange which should be maintained at a certain point in time. This value is fed to the other area.

The changes in the tie-line power flows affected the power balance in corresponding areas as shown in Fig.3. The change in the tie-line power flow over the line connecting the areas 1 and 2

$$\begin{aligned} \mathbf{P_{Tie1\text{-}2}} &= \mathbf{P_{max1\text{-}2} \sin[(\delta_1^o + \Delta\delta_1) - (\delta_2^o + \Delta\delta_2)]} \\ &= \mathbf{P_{max1\text{-}2} [\sin(\delta_1^o - \delta_2^o) \cos(\Delta\delta_1 - \Delta\delta_2) + \cos(\delta_1^o - \delta_2^o) \sin(\Delta\delta_1 - \Delta\delta_2)]} \\ &= \mathbf{P_{Tie1\text{-}2}^o + P_{max1\text{-}2} \cos(\delta_1^o - \delta_2^o) \sin(\Delta\delta_1 - \Delta\delta_2)} \end{aligned} \quad \mathbf{(7)}$$

Where

$P_{max1\text{-}2}$ is the maximum power flow from area 1 to area 2

δ_i^o is the nominal power phase angel of area i

Let the difference phase angle

$$\mathbf{\delta_{12} = \delta_1 - \delta_2} \quad \mathbf{(8)}$$

$\Delta\delta_i$ is the incremental power angle.

The T_{ij}^0 is the Synchronizing coefficient is described by :

$$\begin{aligned} \mathbf{T_{12}^o} &= \mathbf{[P_{Tie1\text{-}2} - P_{Tie1\text{-}2}^o] / ((\Delta\delta_1 - \Delta\delta_2)} \\ &= \mathbf{P_{max1\text{-}2} \cos((\delta_1^o - \delta_2^o)} \end{aligned} \quad \mathbf{(9)}$$

For small incremental angle $\Delta\delta_i$, the tie-line power exchange is

$$\begin{aligned} \mathbf{\Delta P_{tie1,2}} &= \mathbf{T_{12}^0 \sin(\delta_1^0 - \delta_2^0) \cos(\Delta\delta_1^0 - \Delta\delta_2^0) - T_{12}^0 \sin(\delta_1^0 - \delta_2^0)} \\ &\quad \mathbf{+ T_{12}^0 \cos(\delta_1^0 - \delta_2^0) \sin(\Delta\delta_1^0 - \Delta\delta_2^0)} \end{aligned} \quad \mathbf{(10)}$$

$$\mathbf{= T_{12}^0 \sin(\delta_{12}^0) \cos(\Delta\delta_{12}) - T_{12}^0 \sin(\delta_{12}^0) + T_{12}^0 \cos(\delta_{12}) \sin(\Delta\delta_{12}^0)} \quad \mathbf{(11)}$$

Fig. 6 shows the block diagram of the tie – line power exchange .

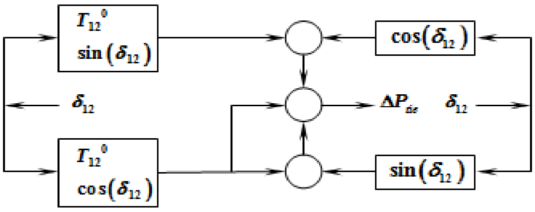

Fig.6 Tie -Line Power Exchange.

IV. Fuzzy Logic Control

A fuzzy system usually takes the form of an iteratively adjusting model. In such a system, input values are normalized and converted to fuzzy representations, the model's rule base is executed to produce a consequent fuzzy region for each solution variable, and the consequent regions are defuzzified to find the expected value of each solution variable [2-8].

On the other hand, a novel methodology Fuzzy logic control system adjusts its control surface in accord with parameters. The system can be made by adding a facility for changing the normalization of the universe of discourse [3-12].

In this section, a systematic method is given to help the designer getting the best of reasoning algorithm that works well with the application required.

Fig. (7) Shows a Fuzzy Logic Controller usually takes the form of an iteratively adjusting model.

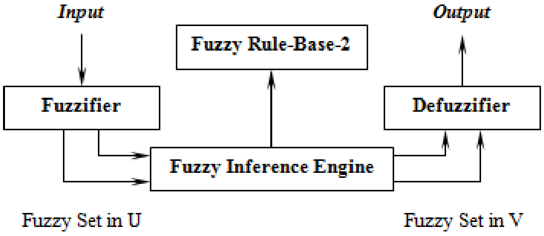

Fig. 7 Fuzzy Logic Control.

In such a system, input values are normalized and converted to fuzzy representations, the fuzzy rule base is executed to produce a consequent fuzzy region for each solution variable, and the consequent regions are defuzzified to find the expected value of each solution variable. The memberships used for both the inputs and the outputs is the standard triangular functions.

The proposed rules depend on the following concepts [7-21] :

- The fuzzy controller maintains the output value, when the output value is set value and the steady state error changes is zero
- Depending on the magnitude and signs of frequency error and frequency error changes, the output value will return to the set value. Table 1 shows a set of decision rules are expressed in linguistic variables relating input signals to the output "control" signal. The input signals are first expressed in linguistic variables using fuzzy notations such as (P) positive, (N) negative, and (Z) zero.

Δe e	N	Z	P
N	**P**	**N**	**Z**
Z	**N**	**Z**	**P**
P	**Z**	**P**	**N**

Table1. Decision Rules for two area fuzzy controller.

The error "e" and the error change " Δe" are defined as a difference between the set point value and the current output value

$e(k) = \Delta P_r^0 (k) - \Delta P_c^0 (k)$ $\Delta e(k) = e(k) - e(k-1)$ (12)

This assumption is satisfied in the following cases:

Case (1)

$e(k) < 0$ and $\Delta e(k) > 0$ $\Rightarrow$

$\Delta P_r^0(k) < \Delta P_c^0(k)$

Case (2)

$e(k) > 0$ and $\Delta e(k) < 0$ $\Rightarrow$

$\Delta P_r^0(k) > \Delta P_c^0(k)$

Where

- **$\Delta P_r^0(k)$ is the reference of the fuzzy logic controller at k-th sampling interval**
- **$\Delta P_c^0(k)$ is the current output value of the controller signal at k-th sampling interval**
- **e(k) is the error signal**
- **Δe(k) is the error change signal**

After the inputs have been fuzzified, the necessary action, i.e. output required is determined from the following linguistics rule:

IF e is "N " AND Δe is "N"
Then u is "P"
IF e is "N " AND Δe is "Z"
Then u is "N"
IF e is "N " AND Δe is "P"
Then u is "Z"
IF e is" Z " AND Δe is "N"
Then u is "N"
IF e is "Z " AND Δe is "Z"
Then u is "Z"
IF e is "Z " AND Δe is "P"
Then u is "P"
IF e is "P " AND Δe is "N"
Then u is "Z"
IF e is "P " AND Δe is "Z"
Then u is "P"
IF e is "P " AND Δe is "P"
Then u is "N"

The proposed programs have been developed to simulate the dynamic behavior of the two-area electric power system. The new controller uses only the available information of the input-output.

V. Simulation Results

In the case of Two Mixed Area Interconnected Power System (TMAIPS), the system parameters are given as follows [2-16].

Area -1 Thermal Area

$M=0.04$: $D=0.01$: $T_g=0.5$: $E=0.03$

Area -2 Hydraulic Area
$M=0.03:D=0.008:T_g=1.2:T_T=0.5:$
$T_w=0.5: E=0.13$

Tie-Line Power
$T_{12}= 0.02701$

The steady state error in the response of two-area Load Frequency Control "LFC" with Fuzzy Logic Control "FLC" is almost zero.

In the case, where area 1 is subjected to a step-load change and the area 2 is disturbance free. It can be seen that, the proposed fuzzy logic controller gives good performance shown in Fig. (8)

The frequency deviation shows the transient response of the thermal area and hydraulic area for a unit step load change in thermal area and free load change in hydraulic area.

The incremental frequency response of the thermal area and hydraulic area are goes to zero value. Fig.(8) shows the transient response of the tie-line power exchange which goes to zero value.

VI. Conclusion

In this paper, the solution of the tie-line control problem, and the problem of the load frequency control of interconnected power systems were discussed. The paper presents a new methodology of a fuzzy logic control strategy to ensure excellent study and guarantees the operation of interconnected power system. The simulation results show that the control performance can be obtained by subjecting a unit step input in one area and no load in the other area.

Therefore with the steady state analysis the performance of the system at specified operating point can be investigated.

Finally, we can conclude that the analysis of the operational characteristics resulted in key findings enabling a further derivation of control algorithms and examination of the fuzzy logic controller under dynamic operating conditions.

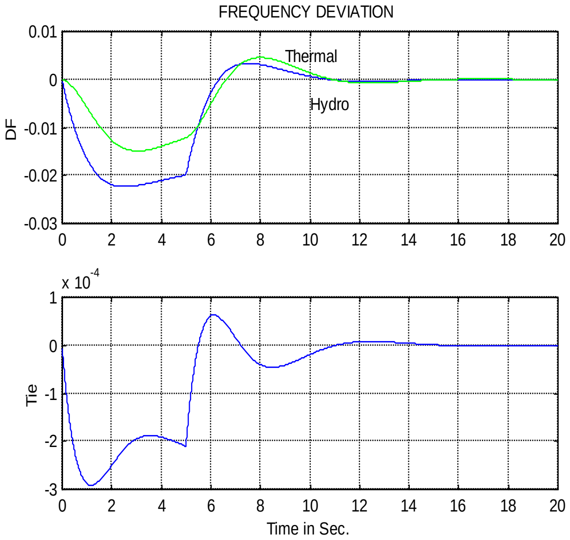

Fig.8 Frequency Deviation of hydraulic and thermal Interconnected Power Systems.

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