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PID-LIKE FUZZY LOGIC CONTROL FOR A TURBOGENERATOR

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Abstract: In this paper, PID-Like fuzzy logic control has designed to control the excitation voltage of a single-input single-output *(SISO)* turbogenerator system connected to an infinite busbar to demonstrate the effectiveness and robustness of these design approach. The performance of this controller is evaluated in comparison with a conventional proportional, integral and derivative *(PID)* controller in simulation. Also, the performance evaluated from the responses to both small and large disturbances, including short circuit on the transmission lines. It is found that, the PID-like fuzzy logic controller is much less sensitive to changes in the operating points of the system. *Copyright © 2000 IFAC*

Keywords: Power Systems, Voltage Control, Regulator, Fuzzy Control, PID Controller, and Conventional Control.

1. INTRODUCTION

During the past several years, there has been a general incorporation of automatization system in a wide range of industrial processes because of necessity of decreasing costs and making the task of the plant operator easier.

The *PID* conventional regulator is the most frequently control element in the industrial world. It is estimated that, at least, the 90% of the controllers employed in the industry are *PID*s or its variations. But it needs a quantitative model of the process; which is not always available. Especially if the process is too complex to achieve a good physical description, conventional methods are not able to guarantee the final control aims, and the controller synthesis has to be based mainly on intuitions and heuristic knowledge. So, expert control strategies have been favored since they are based on the process operator's experience and do not need accurate model.

Over the past two decade, the field of the fuzzy controller applications has broadened to include many industrial control applications (George *et al.*, 1999), and significant research work has supported the development of fuzzy controllers. It is the most successful expert system techniques applied to a wide range of control applications. It has made possible the establishment of "intelligent control". Its attraction, from the process control theory point of view, comes because the fuzzy approach provides a good support for translating the heuristic skilled operator's knowledge about the process and control procedures (expressed in imprecise linguistic sentences) into numerical algorithms.

The investigation of the feasibility of using compositional rule of inference that has been proposed by Zadeh (Zadeh, 1973), for controlling a dynamic plant had pioneered by Mamdani (Mamdani, 1974) in 1974. A year later, Mamdani and Assilian (Mamdani and Assilian, 1975) developed the first fuzzy logic controller *(FLC)*, and it successfully implemented to control a laboratory steam engine plant. In a strict sense, the first fuzzy controller shown in (Mamdani and Assilian, 1975) was equivalent to two-input fuzzy PI *(PI-like)* controllers where error and change of error, were used as the inputs for the inference. The most common and robust fuzzy reasoning method, called Zadeh-Mamdani min–max gravity reasoning had introduced also by Mamdani's pioneering work. Also, a significant number of in-depth theoretical and analytical investigation related to this structure have been reported (Ying, *et al.*, 1990, and Ying, 1993). A different linguistic description of the output fuzzy sets, and a numerical optimization approach had introduced by Takagi and Sugeno (Takagi and Sugeno, 1985) to design fuzzy controller structure.

PI-like fuzzy logic controllers are quite simple, though they are the most widely used in practice and provide similar results to conventional controllers. But in some applications it may be useful to employ more general controllers, which make it easier to reach the system specifications and improve their performance. In this paper, a simple *PID-like fuzzy logic controller* is developed for controlling the excitation voltage of a nonlinear turbogenerator system, the performance of *PID-like fuzzy logic control* is compared with a commonly used proportional, integral plus derivative *(PID)* controller. It is found that *PID-like fuzzy logic controller* is more robust and efficient than *PID* controller in that *PID-like fuzzy logic controller* is much less sensitive to changes in system operating points.

2. TURBOGENERATOR SYSTEM

The system considered in this paper (figure (1)) consists of a turbogenerator unit connected to a large power system by a transformer and two parallel transmission lines (Pullman, 1977 and Shackshaft, 1963). The transmission system may be represented by lumped series resistance and reactance, which can be combined with the impedance of the generator transformer. A thyristor exciter is used because it gives very fast control action. The generator is represented by 7^{th}-order nonlinear mathematical model, and is driven by a three-stage steam turbine with reheat. The turbine can be represented by 6^{th}-order nonlinear mathematical model; each stage consists of a single-time constant element. The re-heater and valve servomechanisms are also described by first-order transfer functions. A 13^{th}-order non-linear mathematical model was used to describe the turbogenerator for the tests reported here.

3. CONVENTIONAL PID CONTROLLER

PID control is commonly used in industrial application systems. Although a *PID* controller is reliable and efficient, its parameters require precise adjustment to obtain optimal performance, and they are heavily dependent on system parameters. The output of a *PID* is given by:

$$u(t) = k_p e(t) + k_i \int_0^t e(t) + k_d \frac{de(t)}{dt} \quad (1)$$

Where $e(t)$ is the error, u is the control signal and k_p, k_i, k_d are proportional, integral and derivative gain constants, respectively.

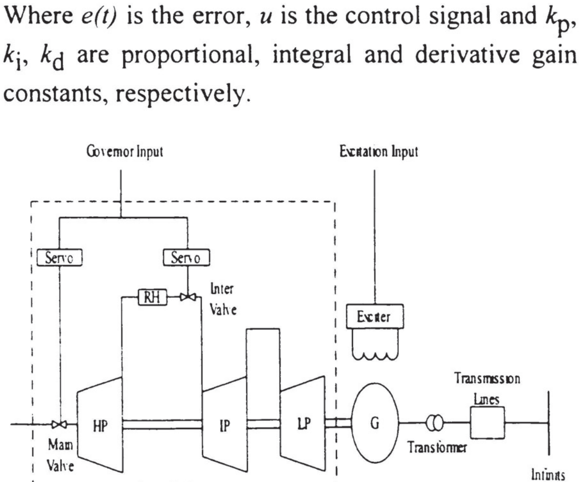

Fig. 1. Turbogenerator System.

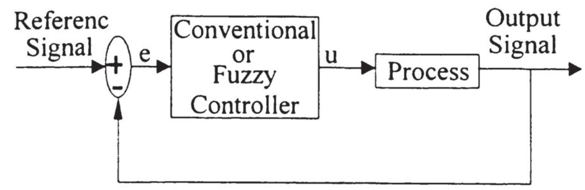

Fig. 2. Cascade Type Feedback Controller

The proportional gain governs the change in the control signal per unit change in the sensor input. The integral term has the effect of continual increase of the control signal as long as the error persists, consequently driving the system to eliminate the error. The derivative term describes the rate of change of the error at a point in time, and therefore promotes a control response, which is much faster than the normal response of excitation system.

4. PID-LIKE FUZZY LOGIC CONTROLLER

The linear *PID* controllers can be classified into different categories with respect to the positioning of the three terms in the closed-loop control system (George, 1999). In computer controlled single-input single-output *(SISO)* plant systems, the cascade-form *PID* controller is commonly used. So that, in this work the classification is restricted to cascade type *PID* controllers as shown in figure (2).

Consider a linear *PID* controller in figure (2), the control signal at any given time instance n with a sampling time T_S can expressed in two forms. Equation (2) shows the absolute form, while equation (3) shows it as a summation of two control actions *PI* control action and *PD* control action:

$$u_{pid}(n) = k_p e(n) + k_i T_s \sum_{q=0}^{n} e(q) + (k_d / T_s)\Delta e \quad (2)$$

$$u_{pid} = u_{pi} + u_{pd} \quad (3)$$

The proposed *PID*-like fuzzy logic control is based on two inputs fuzzy logic controller and combining both *PI* and *PD* actions as shown in figure (3). The rule base structure of this controller is identical to Mamdani-type fuzzy logic controller.

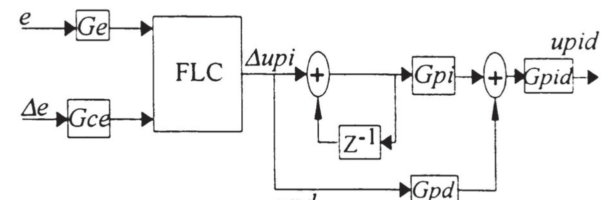

Fig. 3. Two-Inputs PID-Like Fuzzy Logic Controller

Table 1. Applied Fuzzy Control Rules

Error \ Change of Error	NVB	NB	NM	NS	NVS	ZE	PVS	PS	PM	PB	PVB
NVB	NVB	NVB	NVB	NVB	NVB	NVB	NB	NM	NS	NVS	ZE
NB	NVB	NVB	NVB	NVB	NVB	NB	NM	NS	NVS	ZE	PVS
NM	NVB	NVB	NVB	NVB	NB	NM	NS	NVS	ZE	PVS	PS
NS	NVB	NVB	NVB	NB	NM	NS	NVS	ZE	PVS	PS	PM
NVS	NVB	NVB	NB	NM	NS	NVS	ZE	PVS	PS	PM	PB
ZE	NVB	NB	NM	NS	NVS	ZE	PVS	PS	PM	PB	PVB
PVS	NB	NM	NS	NVS	ZE	PVS	PS	PM	PB	PVB	PVB
PS	NM	NS	NVS	ZE	PVS	PS	PM	PB	PVB	PVB	PVB
PM	NS	NVS	ZE	PVS	PS	PM	PB	PVB	PVB	PVB	PVB
PB	NVS	ZE	PVS	PS	PM	PB	PVB	PVB	PVB	PVB	PVB
PVB	ZE	PVS	PS	PM	PB	PVB	PVB	PVB	PVB	PVB	PVB

Given an error *(e)* and change of error *(Δe)*, Mamdani-type fuzzy logic controller can generate a control signal (*u*, act as *PD*-like fuzzy logic controller) or generate an increment control signal (*Δu*, act as *PI*-like fuzzy logic controller) as shown in the following equations:

$$\Delta u_{pi}(n) = k_p \Delta e(n) + k_i T_s e(n) \qquad (4)$$

So, *PI* control action can be calculated as:

$$u_{pi}(n) = u_{pi}(n-1) + \Delta u_{pi}(n) \qquad (5)$$

PD control action can be calculated based on the error and the change of error as following equation:

$$u_{pd}(n) = k_p e(n) + k_d \Delta e(n) \qquad (6)$$

PID-like fuzzy logic controller is formed by combine equation (4), equation (5) and equation (6) as shown in figure (3).

4.1. Mamdani-type Fuzzy Logic Controller (PI-like FLC).

Since fuzzy control theory is somewhat new to those involved in power systems; it is appropriate to review some of the basic concepts. The reader interested in a more comprehensive review of the subject will find (Lee, 1990a, b; Gouda, *et al.* 1997) helpful. In this section, the basic structure of the fuzzy controller, which is shown in figure (4), will be developed. The static fuzzy controller consists of four main functional blocks: fuzzification interface; fuzzy control rules; inference engine, and defuzzification interface.

4.1.1. Fuzzification Interface.

The fuzzification interface consists of the following operations:
(1) Compute the input variables (crisp values of error and change of error).
(2) Perform a scale mapping that transfers the input variable ranges into a corresponding universe of discourse *(quantization/normalization)*.
(3) Perform the fuzzification strategy that converts crisp input data into suitable linguistic variables, which may be viewed as labels of fuzzy sets.

The fuzzification strategy converts the crisp input data into fuzzy sets (linguistic variables) such as, positive very big *(PVB)*, negative very small *(NVS)*, positive big *(PB)*, negative small *(NS)*, zero *(ZE)* and so on. The fuzzification action consists of a set of analogue membership functions, describing the input linguistic terms. The membership function can be of a variety of shapes (e.g. triangle, trapezoid, etc.).

4.1.2. Fuzzy Control Rules.

The dynamic behavior of a fuzzy system is characterized by a set of imprecise conditional statements, which form a set of decision rules.

The process can be expressed linguistically as a set of linguistic decision rules of the form: If *(Conditions are satisfied)* Then *(Action can be inferred)*. There are four ways to derive fuzzy control rules (Mamdani, 1974; Takagi, 1985). Referring to human operators' experiences and knowledge may derive them. Modeling or observing the human operator's control actions may derive them. They may be derived from a fuzzy model of the process or the rules may be learnt by the controller (self-organization).

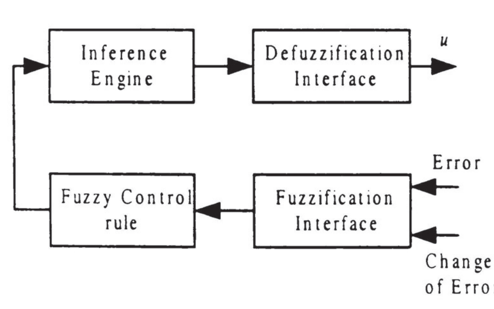

Fig. 4. Structure of a Fuzzy Logic Controller

4.1.3. Inference Engine.

There are in general four methods of fuzzy reasoning (Lee, 1990b). One of the most common methods is used in this work–Mamdani's minimum operation method. The inference mechanism involves the following two functions:

1) Determine for any fuzzy controller input (error and change of error) which rules are applicable.
2) Determine the fuzzy control action by using fuzzy reasoning.

4.1.4. Defuzzification Strategies.

The output of inference engine is a fuzzy set. As a process usually requires a non-fuzzy control signal (crisp value), a defuzzification strategy is needed. There are several methods for defuzzifying to a crisp value (Pedrycz, 1989); the maximum criterion method (*MCM*); mean of maximum method (*MOM*) and the center of gravity method (*COG*). The *COG* method is probably the most common method and is used in this work. This method is based on taking the average of the control action values weighted by the grade of membership.

A fuzzy control algorithm has been developed after some trials in order to verify the fuzzy control rules, membership functions, scaling factors and defuzzification strategy. The detailed structure of the fuzzy controller contains the scaling factors of the error, and the change of error (g_e, g_{ce}).

So the input variables are quantized using different scaling factors of error and change of error. A similar relationship (de-quantize) holds for the control signal which results from defuzzification.

In this application, a fuzzy set is defined by assigning its membership function to (11) fuzzy sets *(NVB, NB NM, NS, NVS ZE, PVS, PS, PM, PB, PVB)* for both the error, change of error and the increment of the control signal as shown in table (1).

Overlapping triangular membership functions were used for inputs (fuzzification) and output (defuzzification), the difference between them being corresponding scaling factors.

Referring to the human operator experience and knowledge derives the fuzzy control rules. There are two selected fuzzy sets each for error and change of error. Therefore, four rules only can be applied which represented by the intersection of two rows and two columns in table (1).

Using Mamdani's minimum operator method for inference, the control action is a fuzzy set which requires a defuzzification strategy to obtain the crisp control signal via the method of centre of gravity *(COG)* to convert from fuzzy values to crisp values. Scaling factors are used to convert the crisp control signals from the normalized discourse to the applied range of actual control signals, which can then be applied to the excitation system.

5. SIMULATION RESULTS

The following results indicate the behavior of the nonlinear *SISO* turbogenerator system with two types of controllers, conventional *PID* controller and *PID-like fuzzy logic controller*. The nonlinear digital simulation of the plant has been adjusted to operate at certain operating point described in terms of active power and reactive power at machine terminals (P_t $=0.8$ p.u, Q_t $=0.2$ p.u.). The principal input to the controller is taken, as the sampled terminal voltage V_T and the reference voltage V_R, with the sampling period is 20 msec. The controllers in turn compute the control signal, which should be applied to the excitation input. Subjecting the system to the following disturbances simulated the nonlinear model of a turbogenerator.

5.1. Terminal Voltage Reference Disturbance.

It is necessary to see how the machine responds to a step change of the reference voltage. Figure (5), show that, when using the conventional *PID* controller, the output terminal voltage follows the reference point but with overshoot. But using the *PID-like fuzzy logic controller,* the terminal voltage follows the reference voltage without overshoot, and smaller rise time than that of the conventional *PID* controller.

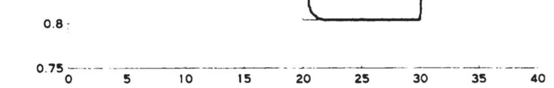

Fig. 5. Terminal Voltage under Conventional *PID* and *PID-like Fuzzy Logic Controller*.

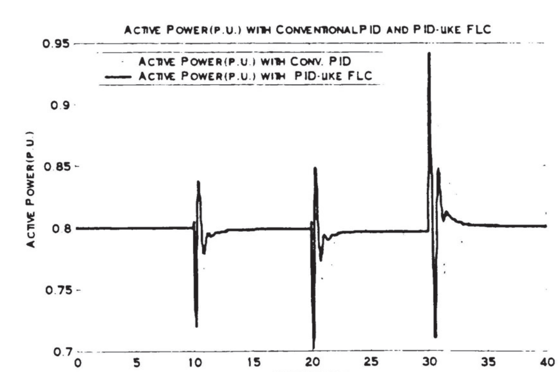

Fig. 6. Machine Active Power under Conventional *PID* and *PID-like Fuzzy Logic Controller*.

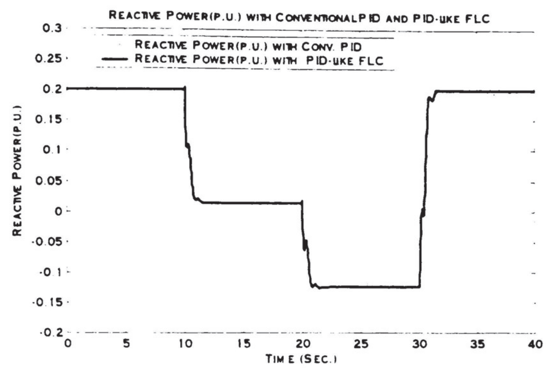

Fig. 7. Machine Reactive Power under Conventional *PID* and *PID-like Fuzzy Logic Controller.*

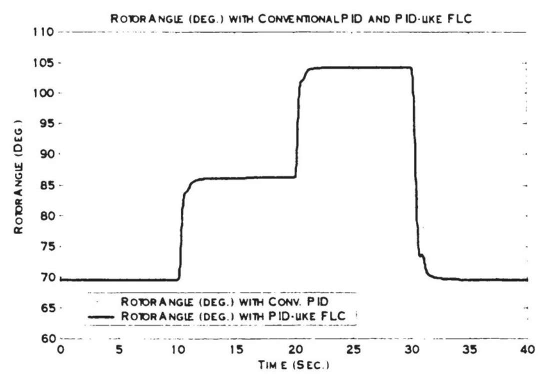

Fig. 8. Machine Rotor Angle under Conventional *PID* and *PID-like Fuzzy Logic Controller.*

Figure (6), show the active power has smaller overshoot and quick damping with the PID-like fuzzy logic controller than the conventional PID controller.

The reactive power response with PID-like fuzzy logic controller shows very little overshoot than with conventional PID controller (figure (7)).

Figure (8), shows the rotor angle with PID-like fuzzy logic controller has no overshoot than with conventional PID controller.

5.2. Short Circuit Test.

A three phase to ground short circuit of 100 ms duration is assumed to occur at the high voltage side of the generator transformer while the input power and reference voltage are kept constant (in this case the reference voltage equal to the steady state value of the terminal voltage). Also the machine is in lagging power factor region with operating point (0.8,02).

Figure (9), shows the terminal voltage with PID-like fuzzy logic controller has smaller overshoot and fast damping than with the conventional PID controller.

Figures (10,11,and 12) show the robustness of the PID-like fuzzy logic controller corresponding to the short circuit test than the conventional PID controller.

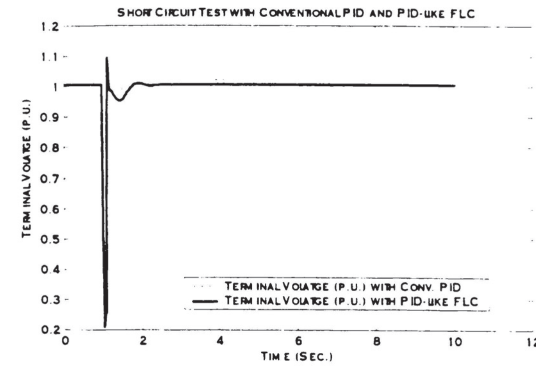

Fig. 9. Short Circuit Voltage under Conventional *PID* and *PID-like Fuzzy Logic Controller.*

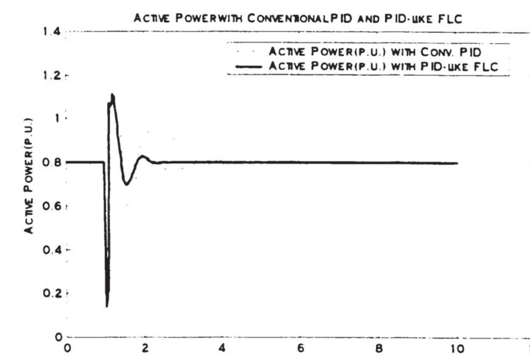

Fig. 10. Active Power under Conventional *PID* and *PID-like Fuzzy Logic Controller.*

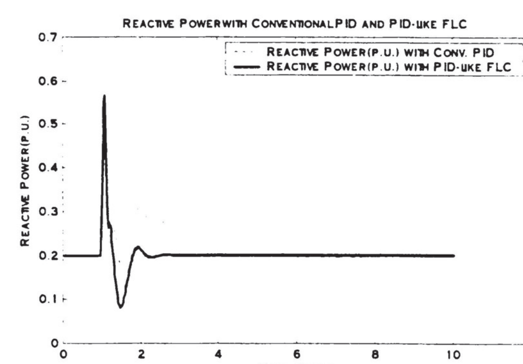

Fig. 11. Reactive Power under Conventional *PID* and *PID-like Fuzzy Logic Controller.*

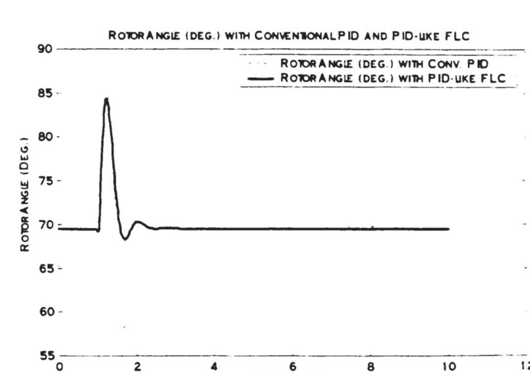

Fig. 12. Rotor Angle under Conventional *PID* and *PID-like Fuzzy Logic Controller.*

6. CONCLUSIONS

This paper describes the using of a simple PID-like fuzzy logic controller based on two-input fuzzy logic controller and combining both *PI* and *PD* actions. From the simulation results, the fixed parameters conventional PID controller needs to be redesigned for each power application and has to be retuned if the system configuration changes.

The PID-like fuzzy logic controller has the capacity to accept imprecision and even vagueness in system parameters.

Thus changes in the system configuration or system parameters should have aminor effect on the performance of the PID-like fuzzy logic controller.

The results obtained confirm that the developed algorithm is powerfull for achieving tracking and regulation objectives.

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