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Design and Implementation of a Fuzzy Logic Controller for Synchronous Generator

Naeim Farouk and Liu Sheng
Harbin Engineering University, College of Automation, Heilongjiang, Harbin, China, 150001

Abstract: The electrical power generation and distribution in power plant suffers from so many problems, such as instability of demand and generation. These lead to increase of generation cost. In this study, self-tuning fuzzy PID controller is developed to improve the performance of automated voltage regulation of a synchronous generator. The controller is designed based on the mathematical model of the system, which is estimated by using system identification technique. Simulation was carried out using Matlab Program to get the output response of the system. In addition, we used root locus methods before and after adding the PID controller. From the results, we conclude that the overall system response was improved significantly when using self-tuning fuzzy PID controller.

Keywords: Fuzzy logic controller, PID controller, root locus, synchronous generator, voltage regulation

INTRODUCTION

In power plants, the generator excitation system preserves generator voltage and controls the reactive power flow using an Automatic Voltage Regulator (AVR) (Ching-Chang *et al*., 2009; Gaing, 2004).

The stability of a synchronous generator that connects to power system would critically affect the security of the power system that depends on the role of AVR.

Synchronous generator excitation control is one of the most important measures to enhance power system stability and to guarantee the quality of electrical power it provides (Darabi *et al*., 2008).

An interconnected power system consists of several essential components. They are namely the generating units, the transmission lines, the loads, the transformer, static VAR compensators and lastly the HVDC lines (Pai, 1981). During the operation of the generators, there may be some disturbances such as sustained oscillations in the speed or periodic variations in the torque that is applied to the generator. These disturbances may result in voltage or frequency fluctuation that may affect the other parts of the interconnected power system. External factors, such as lightning, can also cause disturbances to the power system. All these disturbances are termed as faults. When a fault occurs, it causes the motor to lose synchronism if the natural frequency of oscillation coincides with the frequency of oscillation of the generators. With these factors in mind, the basic condition for a power system with stability is synchronism. Besides this condition, there are other important condition such as steady-state stability, transient stability, harmonics and disturbance, collapse of voltage and the loss of reactive power.

In most modern systems, the AVR is a controller that senses the generator output voltage then initiates corrective action by changing the exciter control in the desired direction.

METHODOLOGY

Excitation control systems: Excitation control of generators is a very important issue in the operation of power systems.

The main control function of the excitation system is to regulate the generator terminal voltage that is accomplished by adjusting the field voltage with respect to the variation of the terminal voltage (Nang and Lwin, 2010).

Classical methods that make use of linear models for designing controllers are valid only on small variation around an operating point.

A number of new control theories and methods have been introduced to design high performance excitation controllers to deal with the problem of transient stability for nonlinear synchronous generator models. Among them the Lyapunov method, singular perturbation methods, feedback linearization and sliding mode control, linear optimal control, the adaptive control method associated with neuro technique, the fuzzy logic control theory (Ramzy and Al-Waily, 2010; Ouassaid *et al*., 2005).

A simplified block diagram of excitation control system as shown in Fig. 1.

Automatic Voltage Regulator (AVR): One of the major auxiliary parts of the synchronous generator is the automatic voltage regulator AVR.

Corresponding Author: Naeim Farouk, Harbin Engineering University, College of Automation, Heilongjiang, Harbin, China, 150001

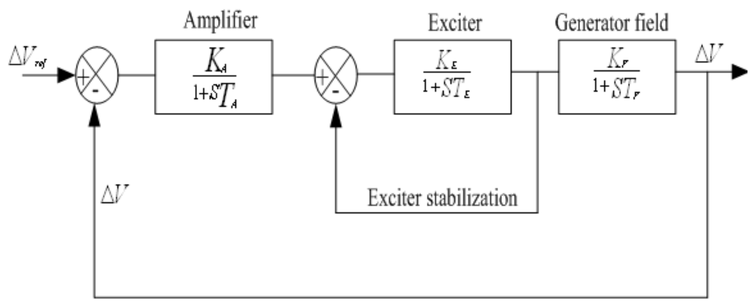

Fig. 1: A simplified block diagram of voltage (excitation) control system

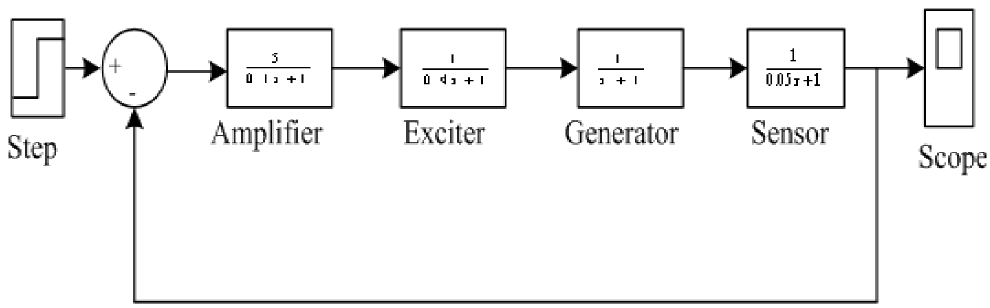

Fig. 2: A simple block diagram of AVR system

It is an important matter for the stable electrical power service to develop the Automatic Voltage Regulator (AVR) of the synchronous generator with a high efficiency and a fast response. Until now, the analog PID controller is generally used for the AVR because of its simplicity and low cost (Leandro Dos Santos Coelho, 2009; Mendoza *et al*., 2007).

The function of the AVR is to maintain the generator terminal voltage at a preset value. Any change in the terminal voltage from the desired value is detected and is used as the actuating signal to control the excitation.

Linearized model of an AVR system: An AVR is used to hold the terminal voltage magnitude of a synchronous generator at a specified level. A simple AVR system comprises four main components, namely amplifier, exciter, generator and sensor. For mathematical modeling and determining transfer functions of the four components, these components must be linearized, which takes into account the major time constant and ignores the saturation or other nonlinearities.

The approximate transfer functions of these components may be represented, respectively, as follows (Ross, 1995).

The simple AVR system model can be expressed by Fig. 2.

Amplifier model: The transfer function of amplifier model is:

$$\frac{V_R(s)}{V_E(s)} = \frac{K_A(s)}{1+T_A(s)} \tag{1}$$

where, the value of K_A is in the range 10 to 400 and the value of the amplifier time constant T_A is in the range 0.02 to 0.1s. In our simulation, K_A was set to 5 and T_A was set to 0.1s.

Exciter model: The transfer function of exciter model is:

$$\frac{V_F(s)}{V_R(s)} = \frac{K_E(s)}{1+T_E(s)} \tag{2}$$

where, the value of K_E is in the range 1 to 200 and the value of the amplifier time constant T_E is in the range 0.5 to 1s. In our simulation, K_E was set to 1 and T_E was set to 0.4s.

Generator model: The transfer function of generator model is:

$$\frac{V_T(s)}{V_F(s)} = \frac{K_G(s)}{1+T_G(s)} \tag{3}$$

Here the constants depend on the load; the value of K_G varies between 0.7 to 1 and generator time constant T_G in the range 1 to 2s from full load to no load. In our simulation, K_G was set to 1 and T_G was set to 1s.

Sensor model: The transfer function of sensor model is:

$$\frac{V_S(s)}{V_T(s)} = \frac{K_R(s)}{1+T_R(s)} \tag{4}$$

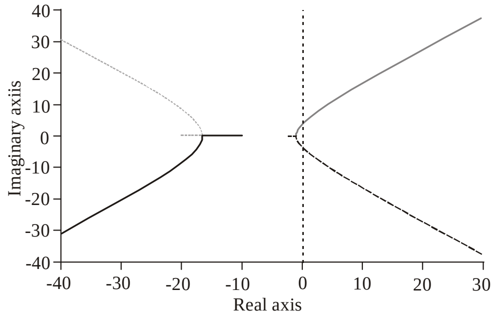

Fig. 3: Root locus of AVR without controller

where, the gain K_R is usually kept 1 and the time constant T_R is very small, ranging from 0.01 to 0.06s. In our simulation, K_R was set to 1 and T_R was set to 0.01s.

SIMULATION RESULTS

Simulation of the AVR without controller: The open loop transfer function of the AVR is:

$$G(S)H(S) = \frac{K_A K_E K_G K_R}{(1+sT_A)(1+sT_E)(1+sT_G)(1+sT_R)} \tag{5}$$

By expanding Eq. (7), we get:

$$G(S)H(S) = \frac{a_1}{a_S{}^4 + b_S{}^3 + c_S{}^2 + ds + 1} \tag{6}$$

We note the system is type four:

$a_1 = K_A\ K_E\ K_G\ K_R$

$a = T_A\ T_E\ T_G\ T_R$

$b = T_A T_E(T_R+T_G)+T_G T_R(T_A+T_E)$

$c = T_A T_E+T_R T_G+T_R T_G(T_A+T_E)$

$d = T_R+T_A+T_G+T_E$

We used the values in Table 1 to obtained the constant a_1, a, b, c and d. The root locus of the system as shown in Fig. 3.

There are two closed poles lies on the jw axis at ±j5 and also two complex conjugate poles on the right half s-plane at s = 6±j10. From these we can conclude that the system will be unstable when closing the loop:

$$G(S)H(S) = \frac{k}{(1+0.1S)(1+0.4S)(1+S)(1+0.05S)} \tag{7}$$

$$= \frac{1.9\left(1+\frac{1}{0.1S}\right)}{(S+10)(S+2.5)(S+1)(S+20)} \tag{8}$$

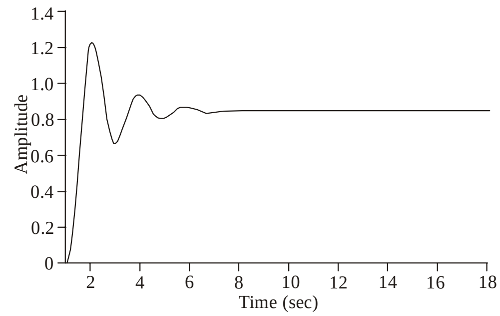

Fig. 4: The step response of the AVR system without controller

Table 1: Root locus result

Root locus	KA	KR	KE	KG	TA	TR	TE	TG	Kd	Kp	Ki	Poles location
Without controller	5	1	1	1	0.1	0.05	0.4	1	-	-	-	S =-1 1 near the jw axis
With controller	5	1	1	1	0.1	0.05	0.4	1	0.35	0.26	0.10	no closed loop poles on jw axis on the right half S plane

The step response of the AVR system without controller as shown in Fig. 4.

Self-tuning fuzzy PID controller: Prof. L.A. Zadeh developed systematic treatment for Fuzzy Logic controller (Hasan *et al*., 1991) and later on Mamdani and Assilian used fuzzy sets with an adaptive feedback control strategy to control a small toy steam engine. This was the first practical applications of Fuzzy Logic Controller (FLC).

In general there are three main types of fuzzy infernece systems such as, Mamdani model; Sugeno model and Tsukamoto model. Out of these three, Mamdani model is the most popular one.

There are also various defuzzification techniques such as: Mean of maximum method, Centroid of area method, Bisector of area methd etc.

Fuzzy logic architecture: The block diagram of fuzzy controller as shown in Fig. 5. The fuzzy controller is composed of the following four elements:

A rule-base: (A set of If-Then rules), which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control.

An inference mechanism: (Also called an "inference engine" or "fuzzy inference" module), which emulates the expert's decision making in interpreting and applying knowledge about how best to control the plant.

Fuzzification interface: Which converts controller inputs into information that the inference mechanism can easily use to activate and apply rules.

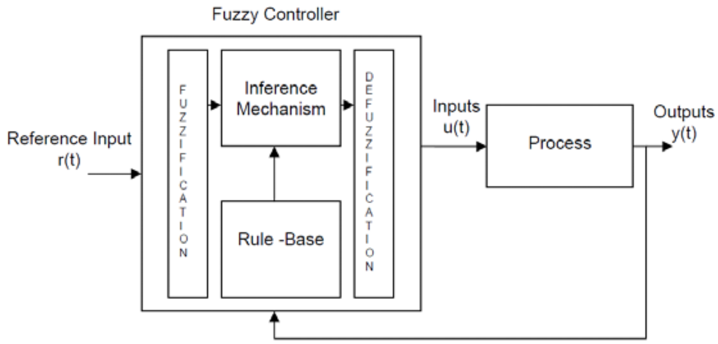

Fig. 5: Block diagram of fuzzy controller

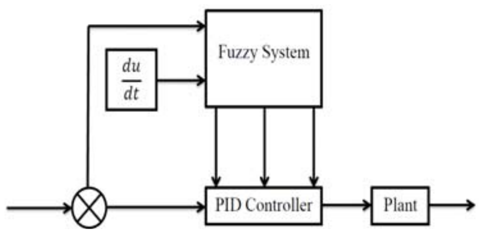

Fig. 6: Basic structure of a fuzzy PID controller

Defuzzification interface: Which converts the conclusions of the inference mechanism into actual inputs for the process.

Design and structure of the self-tuning fuzzy PID controller: The Self-tuning fuzzy PID controller, which takes error "e" and rate of change-in-error "ec" as the input to the controller makes use of the fuzzy control rules to modify PID parameters on-line.

The self tuning of the PID controller refers to finding the fuzzy relationship between the three parameters of PID, K_p, K_i and K_d and "e" and "ec" and according to the principle of fuzzy control modifying the three parameters in order to meet different requirements for control parameters when "e" and "ec" are different and making the control object produce a good dynamic and static performance. Selecting the language variables of "e", "ec", K_p, K_i and K_d is choosing seven fuzzy vlaues (NB, NM, NS, ZO, PS, PM, PB). The region of these varibales, in this case, is taken to be {-3, -2, -1, 0, 1, 2, 3}. Here (NB, NM, NS, ZO, PS, PM, PB) is the set of linguistic values which, respectively represent 'negative big', 'negative medium', 'negative small', 'zero', 'positive small', 'positive medium' and 'positive big'.

The following Fig. 6 is the block diagram of a self-tuning fuzzy PID controller. As it can be seen from the block diagram, the fuzzification takes two inputs (e and ec) and gives three outputs (K_p, K_i, K_d). The structure of fuzzy PID controller as shown in Fig. 6.

In recent years, fuzzy theory has emerged as a powerful tool in various control systems applications. Researchers are starting to use fuzzy control in various power systems application areas (Chung-Ching and Yuan-Yin, 1991; Miranda and Saraiva, 1992).

Simulation results using self-tuning fuzzy PID controller: The rsponse of the fuzzy self-tuning PID controller is obtained using Matlab Program. A two-input and three-output fuzzy controller is created and the membership functions and fuzzy rules are determined. Fuzzy inference block of the controller design as shown in Fig. 7. The membership function of the language variables "e", "ec", K_p, K_i and K_d are in the given range {-3, 3}.

Generally, the fuzzy rules are depended on the plant to be controlled and the type of the controller and from practical experience. The fuzzy rules are composed as follows:

Rule i: If e(t) is A_{1i} and de(t) A_{2i} then

$$K'_p = B_i \text{ and } K'_i = C_i \text{ and } K'_d = D_i \tag{9}$$

where, i = 1, 2, 3,..., n and n is number of rules. We have 7 variables as input and 7 variables as output, hence, in the design we have 49 fuzzy rules. The Matlab Simulink model of AVR system along with fuzzy tuning PID controller as shown in Fig. 8.

The proposed methodology for PID controller tuning was tested on an AVR system. The AVR system consists of amplifier, exciter, generator and sensor.
The closed loop transfer function is:

$$G(S)H(S) = \frac{K_A K_E K_G\left(SK_p + K_i + K_d S^2\right)K_R}{S(1+ST_A)(1+ST_E)(1+ST_G)(1+ST_R)} \tag{10}$$

Root locus: By expanding the above Equ. 10, we get:

$$G(S)H(S) = \frac{a_1 k_d S^2 + a_1 k_p S + a_1 k_i}{aS^5 + bS^4 + cS^3 + dS^2 + S} \tag{11}$$

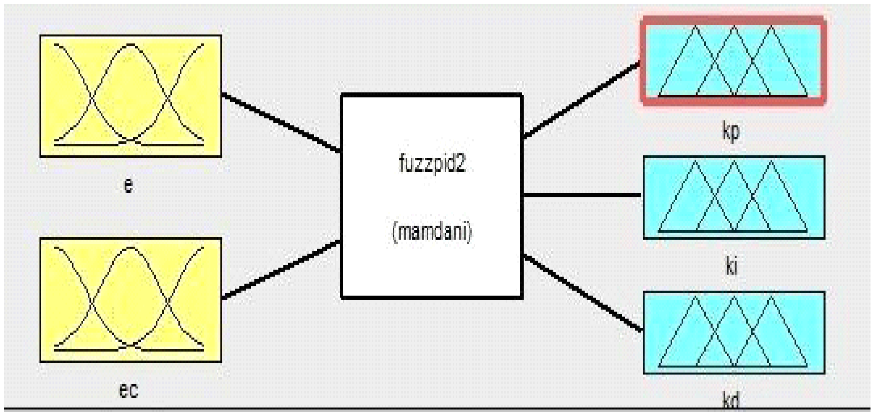

Fig. 7: Mamdani fuzzy system

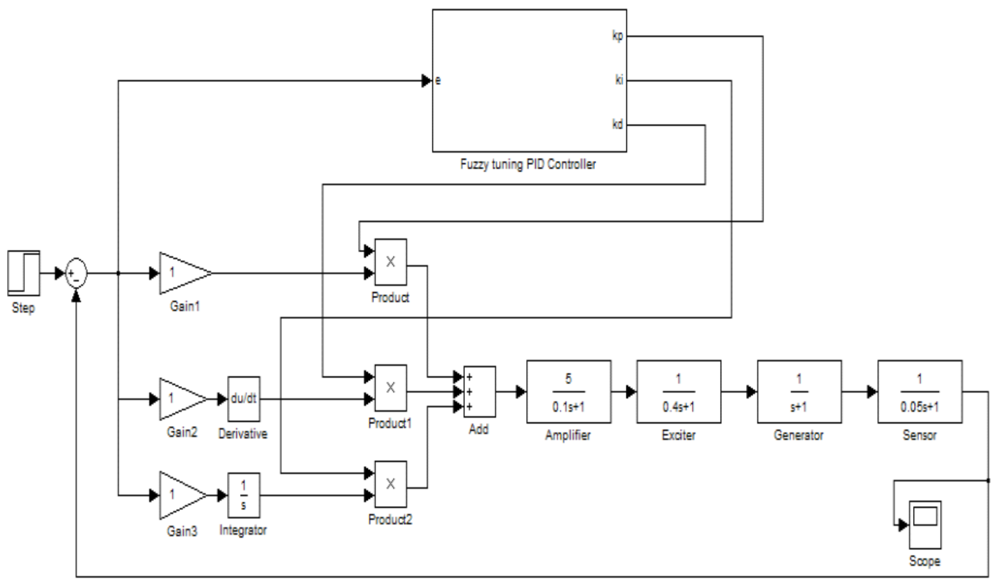

Fig. 8: Block diagram of automatic voltage regulator with fuzzy controller simulated in matlab

$a_1 = K_A\, K_E\, K_G K_R$

$a = T_A\, T_G\, T_R\, T_R$

$b = T_A T_G(T_E+T_R)+T_E T_R(T_A+T_G)$

$c = T_E T_R+T_A T_G$

$d = T_E+T_R+T_G+T_A$

We used the value in Table 1 to obtained the constant a_1, a, b, c and d. The root locus of the system as shown in Fig. 9.

From the result, we conclude that the system is stable, no closed loop poles on the right half-S plane or the jw axis.

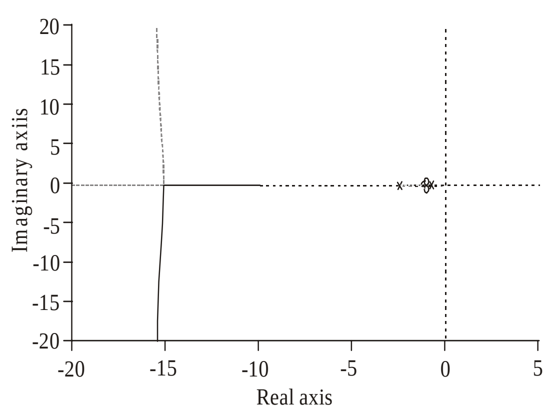

Fig. 9: Root locus of AVR with controller

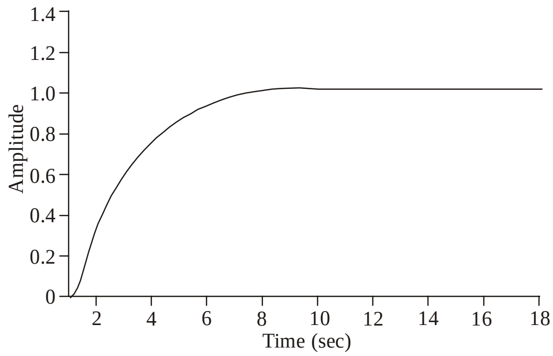

Fig. 10: Step response of the system after adding fuzzy tuning PID controller

Figure 10; display the graphs of the closed loop with best fuzzy tuning of PID controller for the AVR system. As can be seen in Fig. 10, the optimized fuzzy tuning PID controllers produce the good settling time with small or no overshoot and steady state error.

CONCLUSION

The main benefit of designing and implementing a fuzzy controller is the ease of design and flexibility.

In the present study, self-tuning fuzzy controller was applied to tune the value of K_p, K_i and K_d of the PID controller. From the result, we conclude that the overall system response was improved when adding a self-tuning fuzzy PID controller. The improvement was achieved as:

- Reduction in rise time, settling time and overshoot
- Elimination of steady state error

In addition, we use root locus methods before and after adding controller and the results were also compared.

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