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Decentralized Fuzzy PID Excitation controller Combined with Turbine Regulating for Voltage Stability in Power Systems

***Abstract**. This study deals with the design of a decentralized fuzzy proportional–integral–derivative (PID) excitation controller combined with turbine regulating to enhance the voltage stability in power systems after start-up or sudden disturbances. Based on the turbine regulating, we design the fuzzy PID (FPID) excitation controller combined with turbine regulating (FPID-TR). Simulation results show the effectiveness of the proposed controller for stabilizing the voltage in power systems.*

***Streszczenie.** W artykule opisano sterownik PID wzbudzenia połączony z regulacją turbiny zastosowany w celu poprawy stabilności systemu energetycznego przy nagłych zakłóceniach. Sterownik wykorzystuje logikę rozmytą. (**Sterownik PID wzbudzenia połączony z regulacją turbiny w celu poprawy stabilności systemu energetycznego**)*

Keywords: Power System; Mathematical Model; Fuzzy Logic; PID.
Słowa kluczowe: system energetyczny, logika rozmyta, sterownik wzbudzenia.

Introduction

In recent years, the scale of power systems are enlarged gradually, today's power systems are more complex to operate and control. Security is one of the main aspects of an electrical power system, which refers to the ability of the system to withstand disturbances against any violation in system operating conditions. Recently, voltage stability has been considered as a major constraint on secure operation of electric power systems.

Literature survey shows that a lot of work has been done on the voltage stability analysis of transmission systems [1]. Jasmon and Lee [2] and Gubina and Strmchnik [3] have studied the voltage stability analysis of radial networks. They have represented the whole network by a single line equivalent. The single line equivalent derived by these authors [2, 3] is valid only at the operating point at which it is derived. It can be used for small load changes around this point. However, since the power flow equations are highly nonlinear, even in a simple radial system, the equivalent would be inadequate for assessing the voltage stability.

Classical techniques involved in the design of power system stabilizer (PSS) are based on linearized models. The robustness of these PSSs is limited with respect to continuous variations in the operating point, due to the fact that a linearized model is accurate only in the neighborhood of the operating point around which the system is linearized. Thus, a fixed parameter controller based on the conventional control theory [4-6] is not suitable and the limitation of PSS is great.

PID controllers are commonly used in many industrial applications thanks to its essential functionality and structural simplicity. Systematic methods for designing PID controllers have been extensively studied in the literature, including robust design of PID controllers [7, 8]. For PID controller design, the parameter tuning is easy for first order and second order system, but very difficult for high order system and nonlinear system to obtain a group of preferable PID parameters, such as electric power system. Fuzzy control has descriptive ability of expert experience, powerful reasoning and decision ability. Meanwhile, people has accumulated a wealth of experience in control of PID excitation, how to describe the valuable experience by using fuzzy theory, and realize parameter self-adjusting of PID controller by fuzzy reasoning and decision, which is a target in this paper.

In a modern power system, it is usually important to decentralize the control action for individual areas. This leads to a controller with simpler structure which is suitable for practical implementation. In this paper, we mainly discussed the decentralized FPID-TR, and the performance of the controller is compared with conventional PSS (CPSS) method.

Power system dynamical model and turbine regulating

In order to facilitate analysis and research, we consider a SMIB power system. A single machine infinite bus (SMIB) power system qualitatively exhibits important characteristics of the behaviour of multi-machine systems.

The actual dynamic response of synchronous generator in a practical power system when a fault occurs is very complicated. However, the classical third-order dynamical model of power system has been used for designing the excitation controller and can be written as follows [9-11].

Mechanical equations:

$$\dot{\delta} = \omega \tag{1}$$

$$\dot{\omega} = \frac{-D}{2H}\omega + \frac{\omega_0}{2H}(P_m - P_e) \tag{2}$$

Generator electrical equations:

$$\dot{E}_q^{'} = \frac{1}{T_{do}^{'}}(E_f - E_q) \tag{3}$$

Electrical equations:

$$E_q = \frac{x_{ds}}{x_{ds}^{'}}E_q^{'} - \frac{x_d - x_d^{'}}{x_{ds}^{'}}V_s\cos\delta \tag{4}$$

$$P_e = \frac{V_s E_q}{x_{ds}}\sin\delta \tag{5}$$

$$I_q = \frac{V_s}{x_{ds}}\sin\delta = \frac{Pe}{x_{ad}I_f} \tag{6}$$

$$Q_e = \frac{V_s}{x_{ds}}E_q\cos\delta - \frac{V_s^2}{x_{ds}} \tag{7}$$

$$E_q = x_{ad}I_f \tag{8}$$

$$E_f = k_c u_f \tag{9}$$

$$V_t = \frac{1}{x_{ds}}[x_s^2E_q^2 + V_s^2x_d^2 + 2x_sx_dx_{ds}P_e\cot\delta]^{1/2} \tag{10}$$

$$x_{ds} = x_d + x_T + \frac{1}{2}x_1 \tag{11}$$

$$x_{ds}^{'} = x_d^{'} + x_T + \frac{1}{2}x_1 \tag{12}$$

（13） $x_s = x_T + \frac{1}{2} x_1$

The notion description for the variables and parameters described is given in Appendix A. The variability of mechanical power Pm supplied by the prime mover is an important influence factor for the quality of power supply, especially for the voltage stability. Based on the power system dynamical model above, a hydraulic turbine regulating governor has been described in [12], which is one part of our control strategy for voltage stability, and the mathematical model of the turbine regulating governor is show in Fig.1.

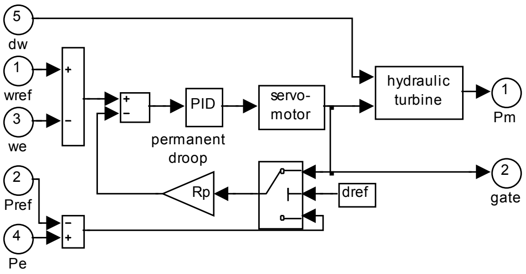

Fig.1. Turbine regulating governor

In Fig.1, the input variables are $wref$, $\Pr ef$, we , Pe , dw , where $wref$ means the desired speed, $\Pr ef$ means the desired electrical power, we means the generator's actual speed, Pe means the generator's actual electrical power, dw means the generator's actual speed deviation with respect to nominal. The output variables are Pm and $gate$, where Pm means the mechanical power to be applied to the generator, $gate$ means the gate opening.

Design of FPID-TR

（A）Design procedure of FLU

The fuzzy logic unit (FLU) is developed to generate the preferable Kp, Ki and Kd for the excitation PID controller. It is a decision maker that operates in a closed-loop system in real time. It receives the required input from generator and processes the data to generate the output. In the proposed method，the fuzzy logic unit will accept the error (e) in terminal voltage and change in error (ec) as inputs, and it will generate the preferable Kp, Ki and Kd for the excitation PID controller as output. The design of the FLU involves: selection of input and output variables, fuzzification of the inputs, development of knowledge base, and defuzzification of outputs.

Step 1 Selection of inputs and outputs

First, we should choose the correct input signals to the FLU. For this unit, choice of input variables, which represent the contents of the rule-antecedent (IF-part of a rule) are selected as (i) error in generator terminal voltage (e), and (ii) change in error (ec). The controller output signal, which represents the contents of the rule-consequent (THEN part of the rule) is the preferable Kp, Ki and Kd for the excitation PID controller. Using previous experience with controller design, the range of variation of error in generator terminal voltage (e) and change in error (ec) are set to their lower and upper limits and then the respective universe of discourse is defined.

Step 2 Fuzzification

Fuzzification interface involves the following two functions:

(i) measures the values of input variables;

(ii) performs the function of fuzzification that converts input data into suitable linguistic values which maybe viewed as labels of fuzzy sets.

To perform fuzzification of inputs, following steps are to be developed in advance.

- The error in generator terminal voltage and change in error is classified as: {negative big(NB), negative medium(NM), negative small(NS), zero(ZO), positive small(PS), positive medium(PM), positive big(PB)}.
- The Kp, Ki and Kd for the excitation PID controller is classified as:{zero(ZO), positive small(PS), positive medium(PM), positive big(PB)}.

After this classification, the fuzzification module can be applied. Each crisp input (either the error or change in error) has several tuples denoted by: {classed fuzzy set and its membership function value}. For example, the type of membership function we selected is triangular, if the error in generator terminal voltage = 0.5, then it has seven tuples as follows: {(NB, 0), (NM, 0), (NS, 0), (ZO, 0.5), (PS, 0.5), (PM, 0), (PB, 0)}.

Step 3 Development of knowledge base

The knowledge base consists of "rule base" and "inference mechanism".

(a) Rule base: The rule base characterizes the control goals and control policy of the domain experts by means of a set of linguistic control rules. The development of decision table includes the formulation of decision rules. Based on the previous experiences of experts and simulation experiments, we obtain 10 essential fuzzy control rules, which are shown as follows:

Rule-1: If(e is NB)then(Kp is PB)and(Ki is ZO)and(Kd is PS)；

Rule-2: If(e is NM)and(ec is NM)then(Kp is PM)and(Ki is PS)and(Kd is PM)；

Rule-3: If(e is NM)and(ec is PM)then(Kp is PM)and(Ki is PS)and(Kd is PM)；

Rule-4: If(e is NS)and(ec is NS)then(Kp is PB)and(Ki is PB)and(Kd is PM)；

Rule-5: If(e is NS)and(ec is PS)then(Kp is PB)and(Ki is PB)and(Kd is PM)；

Rule-6: If(e is PS)and(ec is NS)then(Kp is PB)and(Ki is PB)and(Kd is PM)；

Rule-7: If(e is PS)and(ec is PS)then(Kp is PB)and(Ki is PB)and(Kd is PM)；

Rule-8: If(e is PM)and(ec is NM)then(Kp is PB)and(Ki is ZO)and(Kd is PS)；

Rule-9: If(e is PM)and(ec is PM)then(Kp is PM)and(Ki is PS)and(Kd is PS)；

Rule-10: If(e is PB)then(Kp is PB)and(Ki is ZO)and(Kd is PS).

For example, rule-2 means IF error in terminal voltage is NM AND change in error is NM THEN Kp is PM, Ki is PS and Kd is PM. That is, as a consequence of a fault, if an error in terminal voltage is negative medium (NM) and change in error is negative medium (NM), for the situation in rule-2, the outputs of FLU should be as follows: Kp is positive medium (PM), Ki is positive small (PS) and Kd is positive medium (PM).

(b) Inference mechanism: It has the capability of simulating human decision making based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication. In the FLU we designed, Min. operator is used as fuzzy implication function, and max operator is used as fuzzy aggregation function. For example, according to the Min. operator, the first rule leads to Minimum (degree of membership of NB, degree of membership of PB), where a3 is defined to store the result. Similarly for the other rules calculate a1, a2, a4, . . ., a9, a10.

Step 4 Defuzzification

Based on the inference mechanism, the strength of each membership function of the output can be calculated based on root sum square method. For example, the rules 1, 4, 5, 6, 7, 8, 10 correspond to the output PB for Kp. Now the strength of output PB for Kp is found as follows:

(14) PB_strength= $\sqrt{a1^2+a4^2+a5^2+a6^2+a7^2+a8^2+a10^2}$,

and the other fuzzy output strengths for Kp obtained as :

ZO_strength=0,

PS_strength=0,

(15) PM_strength= $\sqrt{a2^2+a3^2+a9^2}$

Similarly we can obtain the strength of output ZO, PS, PM and PB for Ki and Kd.

As the control action must be a crisp value, the output of the FLU is converted by the center of gravity (COG) method into a single value [13].

$$u=\frac{ZO\_center\times ZO\_strength+PS\_center\times PS\_strength+PM\_center\times PM\_strength+PB\_center\times PB\_strength}{A}. \tag{16}$$

where:

A=ZO_strength+PS_strength+PM_strength+PB_strength,

μ= crisp output.

Based on the FLU designed above, we can obtain the preferable Kp, Ki and Kd, and we denote the three parameters by K_{P_fuzzy}, K_{I_fuzzy} and K_{D_fuzzy}.

（B）FPID control algorithm

For FLU designed above, there are two inputs, e and ec, and three outputs, K_{P_fuzzy}, K_{I_fuzzy} and K_{D_fuzzy}. For fuzzy PID excitation controller, there are five inputs,e, ec, K_{P_fuzzy}, K_{I_fuzzy} and K_{D_fuzzy}, and one output $U(n)$, the control variable $U(n)$ is obtained using the following formula.

$$U(n)=K_{P\_fuzzy}e(n)+K_{I\_fuzzy}\sum_{i=0}^{n-1}e(i)+K_{D\_fuzzy}[e(n)-e(n-1)] \tag{17}$$

$$e(n)=V_{t\_reference}(n)-V_{t\_actual}(n) \tag{18}$$

where $V_{t\_reference}$ means the reference value of generator terminal voltage, and we set $V_{t\_reference}$ =1.0(pu), V_{t_actual} means the actual value of generator terminal voltage.

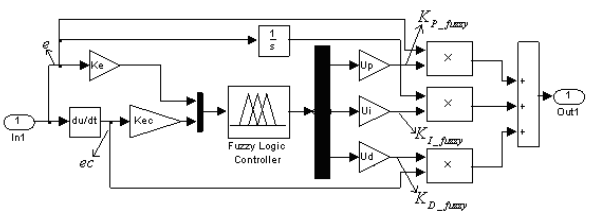

Fig.2. FPID excitation controller

The simulation model of FPID control algorithm is shown in Fig.2. Ke and Kec are quantification factors of e and ec respectively, and Up, Ui and Ud are quantification factors of K_{P_fuzzy}, K_{I_fuzzy} and K_{D_fuzzy} respectively. We have considered these quantification factors as follows: Ke=30, Kec=5, Up=30, Ui=10, Ud=1.

（C）FPID-TR

Classical techniques involved in the design of turbine regulating governor are based on linearized models. The robustness of these turbine regulating governors is limited with respect to continuous variations in the operating point, due to the fact that a linearized model is accurate only in the neighborhood of the operating point around which the system is linearized. Though there are limitations for turbine regulating, but it has effect in voltage stability, so FPID excitation controller with turbine regulating is a good syntaxic method to overcome this problem introduced by fuzzy control techniques. The simulation model of FPID -TR is shown in Fig.3.

The FPID module has been shown in Fig.2, where e_{Vt} can be obtained by equation (18). The TR module is shown in Fig.1. We considered the parameters of TR as follows: Ka=10/3, Ta=0.07s, gmin=0.01, gmax=0.975, vgmin=-0.1, vgmax=0.1, Rp=0.05, kp=1.163, ki=0.105, kd=0, Td=0.01, beta=0, Tw=2.67s.

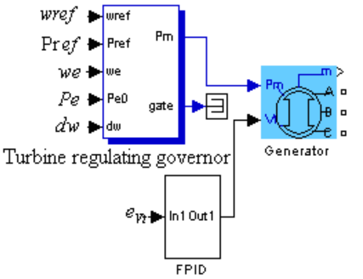

Fig.3. FPID excitation controller combined with turbine regulating

Simulation results and analysis

The purpose of this section is to demonstrate the merits of the proposed FPID-TR. To implement the control method, we have considered the parameters of the SMIB power system [11] as follows: P_n =1110MVA, V_n = 24kV, f_n = 50Hz, x_d = 2.84, x_d' =0.382 , x_q = 2.7, $x1$ = 0.18, R_s = 0.0019097, H=0.1028, F=0.02056, p =2. The operating point of the power system used in the simulations is δ_0 = 72°, P_{m0} = 1.0pu, V_{t0} = 1.0pu. The max system is connected to the generator by a three-phase transformer. The primary voltage of the transformer is 24kV, secondary voltage is 110kV, the winding connection of the transformer is Δ-Yg. The components of three-phase fault, three-phase breaker, and three-phase series RLC branches are shown in Fig.4.

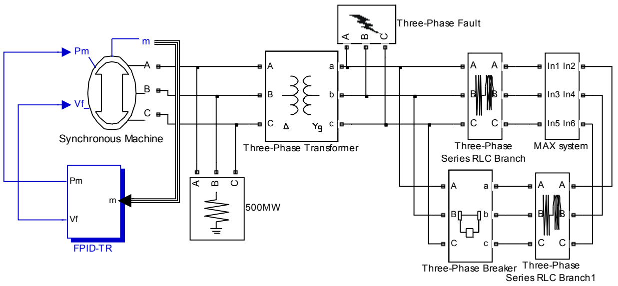

Fig.4. A SMIB power system

In simulation process, we compare the proposed method with the CPSS method in four different cases.

（A）Case 1: start-up stage

In the start-up stage, with the establishment of the field excitation, the power system is in electromagnetic transient process. The oscillation of voltage amplitude is obvious, and controllers can be used to damp the oscillation.

The control effect of CPSS and FPID-TR control methods is shown in Fig.5. From the response of Vt, it can be seen that the control effect of FPID-TR is better than CPSS method. The voltage overshoot of CPSS is 22%, and FPID-TR is 14%. The voltage amplitude adopting FPID-TR is more nearer to the voltage reference value after 3 seconds. After the first oscillation at time 0.4s, there are significant oscillations two times at time 1.5s and 3.9s by adopting CPSS, and there is one time significant oscillation at time 2.1s by adopting FPID-TR.

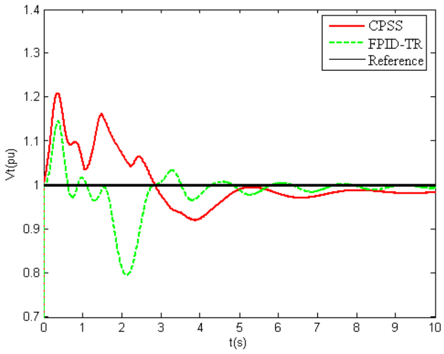

Fig.5. Response of voltage in start-up stage

（B）Case 2: three-phase short circuit fault

The scenario of three-phase short circuit fault is described as follows:

Stage 1 The system is in pre-fault steady state.

Stage 2 A three-phase short circuit fault occurs at 13.0 s.

Stage 3 The fault disappears at 13.1s.

Stage 4 The system is in a post-fault state.

Three-phase short circuit fault is a serious fault to power system, and it can be seen as a big disturbance. When three-phase short circuit fault occurs at 13.0s, the voltage decreases dramatically. When the fault disappears at 13.1s, the voltage restores stability as the control action of controllers.

In Fig.6, it can be seen that FPID-TR has the better control effect after three-phase short circuit fault. By adopting FPID-TR method, the voltage is more nearer to reference value than CPSS method 14.8 seconds later.

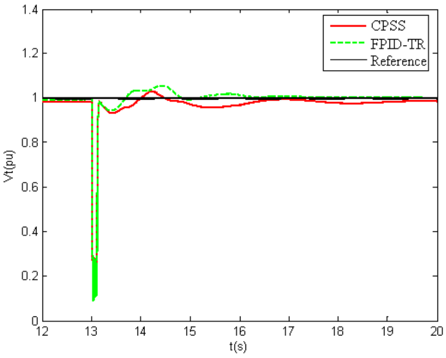

Fig.6. Response of voltage in three-phase short circuit fault

（C）Case 3: mechanical power fluctuation

The scenario of mechanical power fluctuation is described as follows:

Stage 1 The system is in pre-fault steady state.

Stage 2 A disturbance of 0.1pu positive increment of mechanical power occurs at 13.0 s.

Stage 3 The positive increment disturbance of mechanical power disappears at 15.0 s.

Stage 4 The system is in a post-fault state.

In Fig.7, by adopting CPSS method, as the positive increment disturbance of mechanical power occurs, Vt oscillates significantly, and the oscillation lasts for a long time. By adopting FPID-TR method, the voltage oscillation is damped effectively during the mechanical power fluctuation.

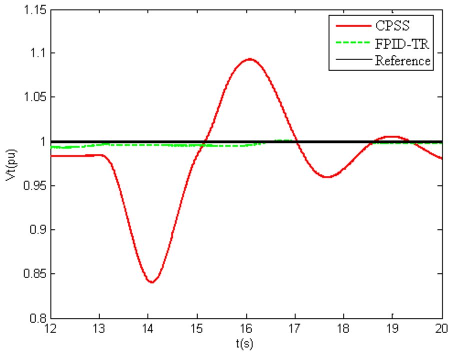

Fig.7. Response of voltage when mechanical power fluctuates

（D）Case 4: switching off of three-phase breaker

The scenario of three-phase breaker switching off fault is described as follows:

Stage 1 The system is in pre-fault steady state.

Stage 2 A three-phase breaker switches off occurs at 10.0s.

Stage 3 The fault disappears at 15.0s.

Stage 4 The system is in a post-fault state.

When the three-phase breaker switches off at 10.0s, voltage amplitude begins to oscillate, the voltage value is more nearer to reference value during the fault period by adopting FPID-TR than CPSS, and the voltage resumes stability rapidly after the fault. By adopting CPSS method, obvious voltage error still exists after the switching off fault, as shown in Fig.8.

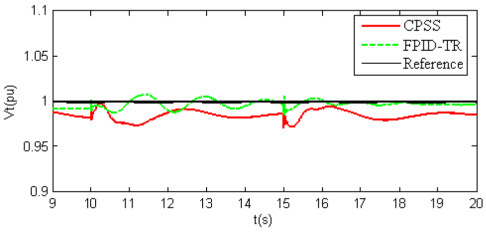

Fig.8. Response of voltage in three-phase breaker switching off fault

Conclusion

In this study, a decentralized fuzzy PID excitation controller combined with turbine regulating scheme has been developed and implemented for a SIMB power system. In start-up process and sudden disturbances, the voltage stability of the proposed scheme is compared with CPSS method. Simulation results show that FPID-TR has better control effect, by adopting FPID-TR control method, the voltage oscillation can be damped more effectively, the voltage reaches to reference value more quickly, and the steady state error is smaller than CPSS method.

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APPENDIX

D damping constant

E_q' internal transient voltage in the q-axis in p.u.

H inertia constant

k_c	amplifier gain of exciter
P_e	active power delivered to the bus in p.u.
P_m	mechanical input power in p.u.
Q_e	reactive power delivered at the terminal of synchronous generator in p.u.
V_t	terminal voltage in p.u.
x_{ad}	the mutual reactance between excitation coil and the stator coil in p.u.
x_d	d-axis synchronous reactance in p.u.
$x_d^{'}$	d-axis transient reactance in p.u.
xl	transmission line reactance in p.u.
x_q	q-axis synchronous reactance in p.u.
x_T	transformer reactance in p.u.
δ	rotor angle of the generator in radian
ω	rotor speed of the generator in rad/s

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