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# Automatic Voltage Regulation of Synchronous Generator with Pole Assignment Self-Tuning Regulator

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*Abstract* : The automatic voltage regulator (AVR) of synchronous generator based on the pole assignment self-tuning regulator is proposed. The poles of the closed-loop transfer function of the system and the poles of the controller are analytically discussed for the stable performance. The response of the AVR system with the saturation characteristics are simulated for the step change of the reference. The validity of the proposed control method is experimentally clarified by using the microprocessor-based control system.

## INTRODUCTION

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 of the synchronous generator because of its simplicity and low cost. In this controller, however, it is necessary to adjust the gains of the PID controller in the field. Furthermore, it can not correspond to the change of its gains when the operating status is varied.

Therefore, the self-tuning PID controller is proposed for adjusting the gains of the PID controller corresponding to the change of performance [1]. Further, the self-tuning controller for the control of the exciter in the synchronous generator [2] and the self-tuning AVR with two sampling time [3,4,5] are proposed. Many approaches to apply the self-tuning control to the AVR of the synchronous generator are implemented.

In this paper, the AVR of the synchronous generator based on the pole assignment self-tuning regulator (PA-STR) [6] is proposed. The poles in the closed-loop transfer function of the system and the poles of the controller are analytically discussed for the stable performance of the system. The response of the AVR system with the saturation characteristics is simulated for the step change of the reference. Then, the validity of the proposed control method is experimentally clarified by using the microprocessor-based control system. It is confirmed that the proposed control system is very available for the AVR of the synchronous generator.

## SELF-TUNING CONTROL AND AVR

### Self-Tuning Control

The self-tuning control that is one of the adaptive control theories has a function of automatically adjusting the control gains corresponding to the change of the parameters of the plant. Fig.1 shows the fundamental construction of the self-tuning regulator with a single input and a single output. In the self-tuning control method, the control algorithm is implemented by the next three steps.

- (a) identification : to identify the plant parameters from the input and output data
- (b) controller synthesis : to decide the control gain on the basis of the result of identification
- (c) control action : to give the control input to the plant

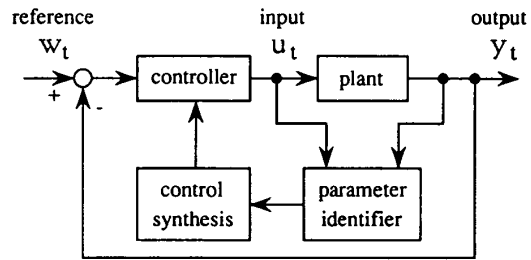


Fig. 1 Fundamental construction of self-tuning regulator

As the identification of the parameters of the plant is carried out on-line, the plant can be controlled well at any time. However, the complicated algorithm is not suitable for the microcomputer-based control system, because it is necessary much time to identify the parameters and decide the control gains. Thus, the sequential minimum square identification and the pole assignment are employed in this paper.

### Pole Assignment Self-Tuning Regulator and AVR

The synchronous generator as a plant is expressed in discrete form by

$$A(z^{-1})y_t = z^{-k}B(z^{-1})u_t \quad (1)$$

where,

$y_t$  : output,  $u_t$  : input,  $z^{-1}$  : backward-shift operator,  
 $k$  : plant delay (=1)

And, the polynomials  $A(z^{-1})$  and  $B(z^{-1})$  is expressed by

$$A(z^{-1}) = 1 + a_1z^{-1} + a_2z^{-2} + \dots + a_nz^{-n} \quad (2)$$

$$B(z^{-1}) = b_0 + b_1z^{-1} + b_2z^{-2} + \dots + b_nz^{-n} \quad (3)$$

where,

$a_1, a_2, \dots, a_n, b_1, b_2, \dots, b_n$  : constants

The PA-STR with the integral factor is shown in Fig. 2. The input of the PA-STR is obtained by

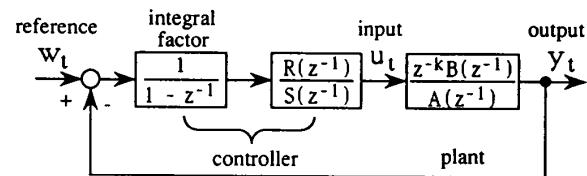


Fig. 2 Block diagram of control system

$$u_t = \frac{R(z^{-1})}{S(z^{-1})(1 - z^{-1})} (w_t - y_t) \quad (4)$$

where,  $w_t$  is the reference. And the polynomials  $S(z^{-1})$  and  $R(z^{-1})$  are expressed by

$$S(z^{-1}) = 1 + s_1 z^{-1} + s_2 z^{-2} + \dots + s_{n_s} z^{-n_s} \quad (5)$$

$$R(z^{-1}) = r_0 + r_1 z^{-1} + r_2 z^{-2} + \dots + r_{n_r} z^{-n_r} \quad (6)$$

where,

$s_1, s_2, \dots, s_{n_s}, r_0, r_1, r_2, \dots, r_{n_r}$  : constants

The denominator in eq.(4) as the forward transfer function of the control system is the characteristic equation of the controller. Then, it is expressed by

$$S(z^{-1})(1 - z^{-1}) = 0 \quad (7)$$

From the block diagram of the control system shown in Fig. 2, the closed-loop transfer function form is obtained by

$$\frac{y_t}{w_t} = \frac{z^{-k} B(z^{-1}) R(z^{-1})}{A(z^{-1}) S(z^{-1}) (1 - z^{-1}) - z^{-k} B(z^{-1}) R(z^{-1})} \quad (8)$$

Then, the characteristic equation of the closed-loop transfer function is expressed by

$$A(z^{-1}) S(z^{-1}) (1 - z^{-1}) + z^{-k} B(z^{-1}) R(z^{-1}) = 0 \quad (9)$$

For the control system in Fig. 2 becomes stable, both of the characteristic equations of the controller and the closed-loop transfer function should have the stable roots.

Then, the polynomial that is preselected as the characteristic equation of the closed-loop transfer function is defined by

$$T(z^{-1}) = 1 + t_1 z^{-1} + t_2 z^{-2} + \dots + t_{n_t} z^{-n_t} \quad (10)$$

where,

$t_1, t_2, \dots, t_{n_t}$  : constants

The coefficients of eq.(10) are decided in advance so as to have the stable roots. In the pole assignment self-tuning regulator, the coefficients of eq.(9) are compared to be equal to the coefficients of eq.(10). Thus, the coefficients of  $S(z^{-1})$  and  $R(z^{-1})$  are obtained. The orders of the polynomials  $R(z^{-1})$  and  $S(z^{-1})$  must be

$$n_r = n_a \quad (11)$$

$$n_s = n_b + k - 2 \quad (12)$$

and the number of closed-loop poles  $n_t$  must satisfy the next equation.

$$n_t \leq n_a + n_b + k - 1 \quad (13)$$

#### POLE ASSIGNMENT AND STABILITY

This paper deals with the AVR of the synchronous generator when the number of the assigned poles is one, two or three. From the synchronous generator in the experiment, the plant is expressed by

$$(1 + 1.2z^{-1} - 0.225z^{-2})y_t = (-0.0531z^{-1} + 0.0723z^{-2})u_t \quad (15)$$

Where  $n_r=2$  and  $n_s=1$  from eqs.(11) and (12). Thus, the eq.(4) is rewritten as

$$u_t = \frac{r_0 + r_1 z^{-1} + r_2 z^{-2}}{(1 + s_1 z^{-1})(1 - z^{-1})} (w_t - y_t) \quad (16)$$

For the characteristic equation of the controller has the stable roots,

the next expression must be satisfied.

$$-1 < s_1 < 1 \quad (17)$$

Table 1 shows the pole ( $s_1$ ) of the controller in the case of one-pole ( $p_1$ ) assignment. Then,  $s_1$  is greater than an unity at all the values of  $p_1$ . Therefore, we can not obtain the stable system in this case.

Tables 2 and 3 show the poles ( $s_1$ ) of the controller in the case

Table 1 Pole of control system with one-pole assignment

$p_1$	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$s_1$	17.621	16.131	14.641	13.151	11.661	10.170	8.680	7.190	5.700

Table 2 Pole of control system with two-poles assignment ( $p_{21}=0.8$ )

$p_{22}$	0.1	0.2	0.3	0.4	0.5	0.6	0.7
$s_1$	6.567	5.944	5.321	4.698	4.075	3.452	2.829

Table 3 Pole of control system with two-poles assignment ( $p_{21}=0.9$ )

$p_{22}$	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
$s_1$	5.185	4.671	4.156	3.641	3.127	2.612	2.098	1.583

Table 4 Pole of control system with three-poles assignment ( $p_{31}=0.8$ )

pole	$p_{33}$							
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	
$p_{32}$	0.1	5.989	5.412	4.834	4.256	3.679	3.101	2.523
	0.2	5.412	4.879	4.347	3.815	3.282	2.750	2.217
	0.3	4.834	4.347	3.860	3.373	2.886	2.399	1.912
	0.4	4.256	3.815	3.373	2.931	2.489	2.048	1.606
	0.5	3.679	3.282	2.886	2.489	2.093	1.697	1.300
	0.6	3.101	2.750	2.399	2.048	1.697	1.345	0.994
	0.7	2.523	2.217	1.912	1.606	1.300	0.994	0.689

Table 5 Pole of control system with three- poles assignment ( $p_{31}=0.9$ )

pole	$p_{33}$								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	
$p_{32}$	0.1	4.708	4.231	3.754	3.277	2.799	2.322	1.845	1.368
	0.2	4.231	3.791	3.351	2.912	2.472	2.032	1.592	1.153
	0.3	3.754	3.351	2.949	2.547	2.145	1.742	1.340	0.938
	0.4	3.277	2.912	2.547	2.182	1.817	1.452	1.087	0.722
	0.5	2.799	2.472	2.145	1.817	1.490	1.162	0.835	0.507
	0.6	2.322	2.032	1.742	1.452	1.162	0.872	0.582	0.292
	0.7	1.845	1.592	1.340	1.087	0.835	0.582	0.330	0.077
	0.8	1.368	1.153	0.938	0.722	0.507	0.292	0.077	-0.138

of two-poles assignment. The one pole  $p_{21}$  of the closed-loop transfer function is assigned to be 0.8 and 0.9 in Table 2 and 3, respectively. Then, we can not obtain the stable system in this case because  $s_1$  is greater than an unity at all the values of  $p_{22}$ .

Tables 4 and 5 show the pole ( $s_1$ ) of the controller in the case of three-poles assignment. The one pole  $p_{31}$  of the closed-loop transfer function is assigned to be 0.8 and 0.9 in Table 4 and 5, respectively. In these tables, the root in the shadowed parts is greater than an unity and then the system in this case is unstable. On the other hand, we can obtain the stable system provided that the poles  $p_{32}$  and  $p_{33}$  are selected so as to make  $s_1$  less than an unity.

### SIMULATION

The synchronous generator system has the non-linear characteristics. Then, the saturation characteristic of the synchronous generator system is illustrated as shown in Fig. 3 and this curve is approximated [7] by

$$V_{fe} = V_t(1 + mV_t^n) \quad (18)$$

where,

$V_{fe}$  : field voltage of exciter,  $V_t$  : terminal voltage of generator,  
 $m$  : saturation coefficient,  $n$  : constant

The saturation characteristic is approximated by selecting the values of  $n$  and  $m$ . In the tested synchronous generator system,  $m$  is 0.29 and  $n$  is 4. Table 6 shows the ratings of the tested synchronous generator and the exciter.

Fig. 4 shows the block diagram of the synchronous generator and the exciter. In this figure,  $T_e$ ,  $K_e$ ,  $T_g$  and  $K_g$  are the time constants and the gains of the exciter and the synchronous generator, respectively. As the plant is the self-excited synchronous generator, the input of the exciter is the product of the manipulated variable from the controller and the output voltage of the synchronous generator. The tested synchronous generator and the exciter has the time constants of  $T_g=0.57$  and  $T_e=0.05$ , and then  $K_g$  and  $K_e$  are obtained from the curve in the saturation characteristic.

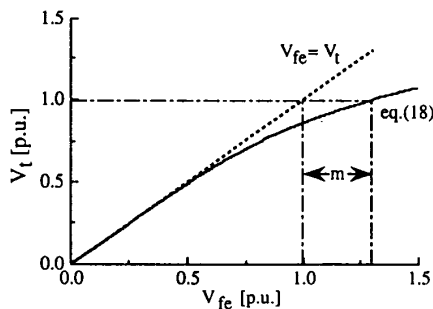


Fig. 3 Saturation characteristic

Table 6 Ratings of tested synchronous generator and exciter

term		generator	exciter
rated kVA	kVA	20	3
rated line-to-line voltage	V	220	110
rated line current	A	52.5	15.75
rated speed	rpm	1800	1800
output frequency	Hz	60	420

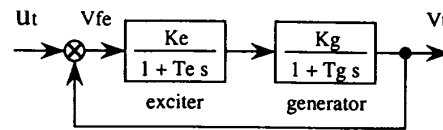


Fig. 4 Block diagram of plant model

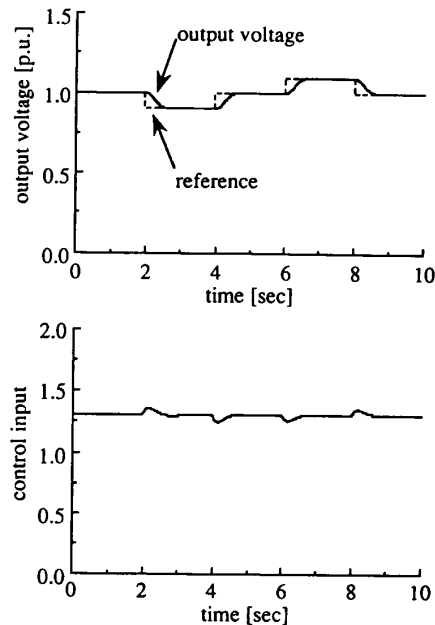


Fig. 5 Step response for three-poles assignment in simulation

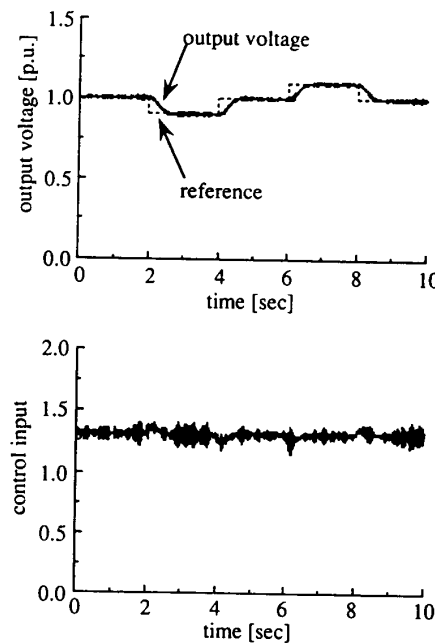


Fig. 6 Step response with white noise in simulation

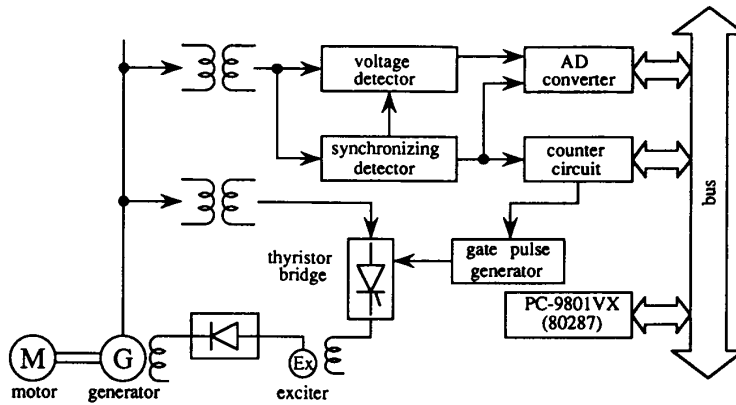


Fig. 7 Experimental system

Fig. 5 shows the step response of the system for the three-poles assignment. The assigned poles of the closed-loop transfer function are 0.9, 0.7 and 0.6. The pole of the controller is 0.582. Namely, all the poles of the system are located to be within an unity circle. Thus, we can obtain the good and stable step response without the overshoot as shown in Fig. 5.

Next, we examine the step response of the output voltage with the white noise. Fig. 6 shows the step response of the system for the three-poles assignment. The control input is the firing angle of the thyristor in the rectifier for the exciter control. The control input of the system is affected by the white noise as shown in Fig. 6. However, the output voltage of the synchronous generator is following well the reference change. Therefore, it is considered that the proposed AVR system is stable in the case of three-poles

assignment. On the other hand, the system with the white noise in the case of the one- and two-poles assignment becomes unstable. Then, the response of the system does not follow the reference change.

#### EXPERIMENT

Fig. 7 shows the experimental system. The ratings of the synchronous generator and the exciter are listed in Table 6. The output voltage of the exciter is regulated by adjusting the firing angle of thyristor in the rectifier. The synchronous generator is a self-excited AC one. The control system is composed of the microcomputer with a 16-bits microprocessor (80286) and co-processor (80287), the AD converter and the counter. The output voltage control is implemented every cycle (16.7ms) by detecting the output voltage of the synchronous generator.

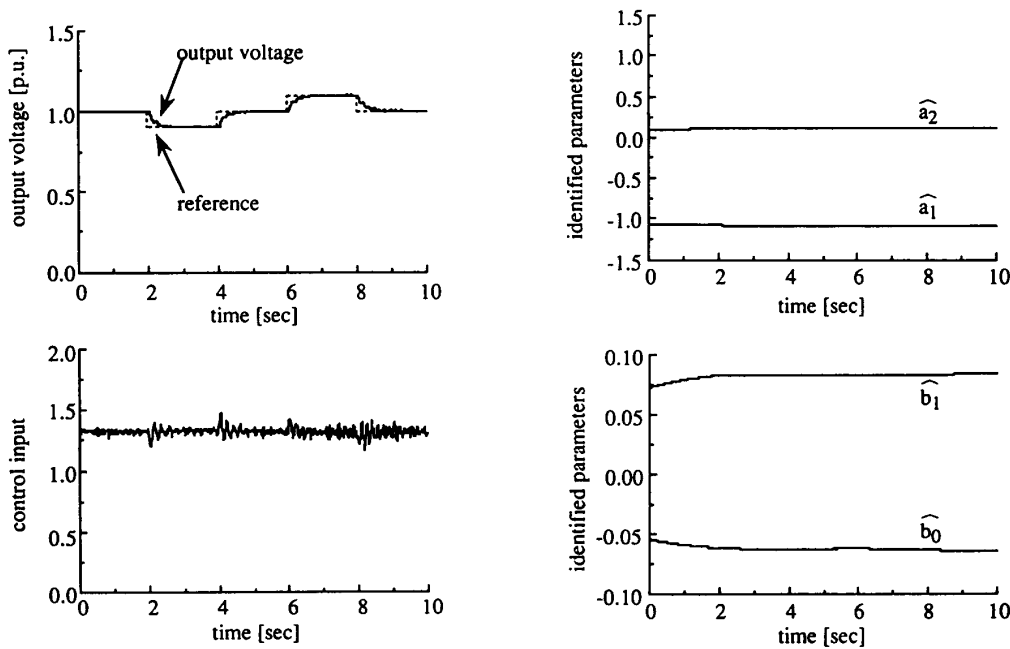


Fig. 8 Step response for three-poles assignment in experiment

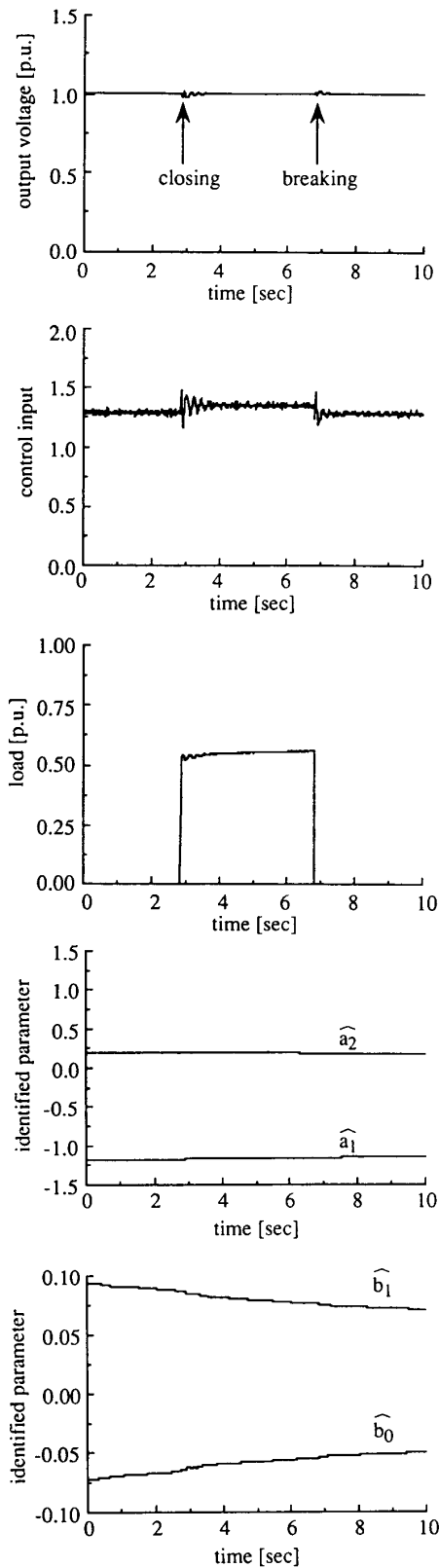


Fig. 9 Response for breaking and closing load in experiment

Fig. 8 shows the response of the output voltage, the control input and the identified system parameters with no load for the step change of the reference. The assigned poles of the closed-loop transfer function are 0.9, 0.7 and 0.6 which are the same in the simulation. The pole of the controller is also 0.582. We can obtain the stable response of the output voltage and the control input as well as the results obtained in the simulation. In the experiment, however, the oscillation due to the noise superimposes the input of the plant. The parameters of the system are identified well and become the constant values. The change of the identified parameters is very small when the reference steps up and down because the forgetting factor used in the least-squares identification is a unity.

Fig. 9 shows the response of the output voltage, the input of the plant and the identified system parameters for the breaking and closing load. The closing load is 56 % of the rated output power of the synchronous generator. During the period after the closing and the breaking load, there is small variation in the output voltage. However, the output voltage is maintained at the rated voltage within 0.5 sec. In this experiment, the system parameters are also identified well as shown in Fig. 9.

Thus, it is confirmed by the experiment that the proposed AVR based on the three-poles assignment self-tuning regulator is very available.

#### CONCLUSIONS

The AVR of the synchronous generator is proposed based on the pole assignment self-tuning regulator. The stable response to the step up/down command of the output voltage are discussed by the simulation and the experiment. Furthermore, the response of the system for the closing and breaking load is discussed in the experiment.

In the discussion of the number of the assigned poles, the system becomes stable in the three-poles assignment. On the other hand, the system is not stable in the case of one- or two-poles assignment. Further, the stable response of the plant is clarified by the simulation of the system with the white noise. The results in the simulation are confirmed by the experiment using the microprocessor-based control system. Then, it is clarified that the proposed control method is very available for the AVR of the synchronous generator.

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