Control Design of Automatic Voltage

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Control Design of Automatic Voltage Regulator to Improve the Voltage Stability at Sengkang Power Plant, South Sulawesi Indonesia

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Abstract. The change in voltage at the generator terminal is highly correlated with the change in reactive power at the center load. There are several reactive power sources in the power system including those from field amplifiers that are controlled by equipment called Automatic Voltage Regulators (*AVR*). Changes in reactive power in the system will change the voltage profile including the voltage at the generator terminal. To maintain the voltage level on the generator terminal, the *AVR* must be adjusted properly. Determination of the value of the amplifier gain on the *AVR* largely determines the performance of the *AVR* in stabilizing the voltage. Wind Turbine penetration greatly affects the system voltage. This research is to see the impact of voltage changes due to wind turbine penetration in sulseltrabar interconnection systems. Determination of *AVR* gain is generated from the Routh-Hurwitz equation. Furthermore, in this study PID control will be applied to increase the *AVR* output response. Determination of the correct *Kp*, *Ki* and *Kd* constants is obtained with the help of a MATLAB simulation model. The simulation shows that using a *PID* controller, the overshoot and settling times obtained are better. The maximum exceeded voltage is 1 per unit and the settling time is 10.15 seconds.

1. Introduction
Voltage stability in the power system is highly correlated with changes in reactive power in the system. The voltage collapse phenomenon is strongly influenced by systems that lack reactive power and control devices fail in the power system [1-3]. Reactive power comes from generator excitation as well as from reactive power compensation equipment such as capacitors and Flexible Alternating Current Transmission Systems (*FACTS*) devices [4-5].

An *AVR* is designed to maintain the terminal voltage of a generator. By adjusting the amplification current in the excitation, the terminal voltage can be controlled. When the system load increases, the voltage at the generator terminal will drop. By increasing the existing supply current, the generator voltage can be increased to a predetermined value. When generators work together in an interconnection system, the AVR on each generator will receive a command signal according to the change in voltage that occurs on the generator bus [6].

In the sulseltrabar interconnection system, wind turbine has entered the system. There are two wind turbine plants namely Sidrap Wind Turbine with a capacity of 75 MW and Tolo Wind Turbine with a capacity of 72 MW. Penetration of the wind turbine in the system will cause problems including the problem of voltage stability [7]. Intermittency of wind turbine does not affect the stability of the voltage so that the performance of the AVR to stabilize the voltage is needed. To improve AVR performance, a control method is needed. In this study PID (Proportional, Integral, Derivative) control is used as a control device [8].

2. Voltage Stability

In electric power systems which are operated in stress conditions, voltage stability becomes very important [9]. In the planning and operation of power systems, stress stability analysis focuses on two aspects including:

1. Prediction, how close are the unstable voltage condition systems.
2. The mechanism, when voltage instability occurs.

Predictions provide a measure of voltage safety, while the mechanism will provide important information that is useful in the operation strategy in preventing voltage instability [10]. The problem of voltage drop is a serious problem in the electrical system in many countries and this occurs in the system of interconnecting electricity. There are several factors that can cause voltage drops including: load increase, lack of excitation, loss of compensation equipment such as capacitors.

2.1. Voltage Settings

In practice, the reactive power supplied by the generator to the load continues to change. This causes the output voltage (voltage on the generator terminal) to be changed to guarantee the generator. it remains stable in compensating for the power requirements at that load. To regulate the size of the output voltage (V_t) that is by adjusting the size of the induced electromotive force (E) generated, by changing the amount of rotor flux (φ) where the magnitude of the rotor flux depends on the magnitude of the reinforcement current so that it can be said that to change the output voltage can be done by change the reinforcement current. If the output voltage exceeds the proper voltage, the gain current must be reduced so that the voltage drops again. Conversely, if the output voltage drops, the amplifying current must be increased so that the voltage returns to normal. In this strengthening current regulation system, there are two conditions that may occur, namely:

a. Under Excitation

Under excitation condition is a generator condition where the gain is less (less strengthened) so that the current will supply to the system. This can be reviewed according to the GGM / flux of the anchor reaction. When the generator is less amplified, it must provide an overtaking current to the system because the overtaking current will produce an anchor flux which will strengthen the rotor flux. The vector notation for under excitation conditions is as follows:

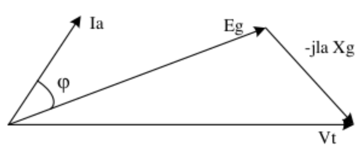

Figure 1. Vector diagram of under excitation conditions

b. Over Excitation

Over excitation condition is a generator condition where the gain is too large (too strengthened) so that it will supply the lagging current to the system. When the generator is too amplified, it must provide a lagging current to the system because the lagging current will produce an anchor flux that will fight the rotor flux to reduce too much gain. The vector notation for over excitation conditions is as follows:

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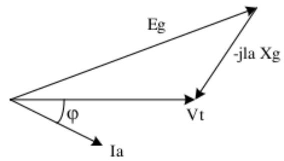

Figure 2. Vector diagram of over excitation conditions

2.2. AVR (Automatic Voltage Regulator)

AVR (Automatic Voltage Regulator) is a device mounted on a generator that can work automatically regulating the voltage or amplitude of the waves produced by the generator to remain stable. *AVR* works in regulating the generator output voltage by controlling the gain current of the generator [11].

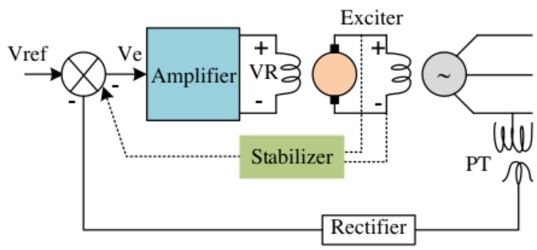

Figure 3. AVR Model

2.1.1. Amplifier

The reinforcement of the excitation system can be in the form of magnetic gain, loop gain, or electronic gain. Amplifiers can be represented as K_A with T_A time constants, which in the mathematical model are like the following equation:

$$\frac{V_R(S)}{V_e(S)} = \frac{K_A}{1+T_A S} \tag{1}$$

The value of the time constant (T_A) is very small, ranging from 0.02 to 0.1 seconds.

2.1.2. Exciter

Excitation commonly used in a generator there are several types ranging from using DC generators to modern types using *SCR* as a rectifier to produce DC power. Excitation can be represented as K_E with T_E time constant, which in its mathematical model is like the following equation:

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

2.1.3. Generator

The terminal voltage of a generator is very dependent on the load. In a linear form, the relation of the terminal voltage function to the field voltage can be represented as K_G with the T_G time constant and the transfer function as follows:

$$\frac{V_t(S)}{V_F(S)} = \frac{K_G}{1+T_G S} \tag{3}$$

2.1.4. Sensor

The sensor consists of a voltage transformer (*VT*) and a rectifier. The sensor can be represented as K_R with the T_R time constant and its transfer function as follows:

$$\frac{V_S(S)}{V_t(S)} = \frac{K_R}{1+T_R S} \tag{4}$$

The working principles of the *AVR* are as follows:

- The generator output voltage is initially reduced by using PT (Potential Transformer) or the voltage transformer then rectified.
- The results of the rectification are then compared with the reference voltage (V_{ref}).
- If a difference occurs, the *AVR* will instruct the amplifier to increase or decrease the DC generator gain current so that the output voltage of the generator also changes.
- If the DC generator output voltage changes, the synchronous generator gain current also changes, consequently the generator output voltage returns stable [12].

The block diagram of an *AVR* is as shown below:

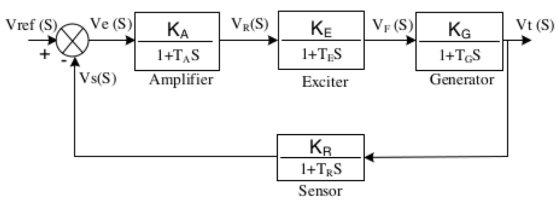

Figure 4. Block diagram of *AVR*

3. Proportional Integral Derivative

The *PID* controller (Proportional Integral Derivated) actually consists of three types of controllers that are mutually combined namely the *P* (Proportional) controller, the *I* controller (Integral), and the *D* controller (Derivative). Each has certain parameters that must be set to operate properly, called constants.

A. P Controller (Proportional)

Proportional controller has an output that is proportional to the size of the error signal/error. In simple terms it can be said that the output of the Proportional controller is the multiplication of proportional constants (*Kp*) with the input signal. A change in the input signal causes the system to directly change its output by its multiplying constant.

Experimentally, the use of Proportional controllers must pay attention to the following conditions:

1. If the K_p value is small, the Proportional controller is only able to make small error corrections, so that it will produce a slow system response.
2. If the K_p value is increased, the system response shows the faster it reaches its steady state.
3. However, if the K_p value is enlarged until it reaches an excessive price, the system will work unstable or the system response will oscillate.

B. Controller I (Integral)

The Integral Controller functions to produce a system response that has a zero steady state error. If the error signal does not change, the output will remain as before the input change occurred. Experimentally, the use of an Integral controller has the following characteristics:

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1. The controller output requires a certain amount of time, so it tends to slow down the response.
2. If the error signal is zero, the controller output will remain at the previous value.
3. If the error signal is not zero then the output will show an increase or decrease which is affected by the magnitude of the error signal and the value of the Integral constant (K_i).
4. Large value Integral Constants (K_i) will accelerate the loss of offset, but will result in an increase in oscillation of the controller output signal.

C. *Controller D (Derivative / Differential)*
A sudden change in input from the Derivative controller will result in very fast and large changes. Experimentally, the use of Derivative controllers has the following characteristics:

1. This controller will not produce output if there is no change in the input (in the form of an error signal).
2. If the error signal changes with time, the output produced by the controller depends on the value of the Derivative constant (K_d) and the rate of change of the error simyal.
3. Derivative controller has a character to overtake, so that this controller can produce a significant correction before the error gets bigger, so it is used to speed up the initial response of a system, although it does not minimize errors in its steady state.

It can be said that each of the *P*, *I*, and *D* controllers has advantages and disadvantages. So that if the three are combined in parallel into a Proportional plus Integral plus Derivative controller or commonly called a *PID* controller, they will overlap. The controlling elements *P*, *I*, and D respectively aim to accelerate the reaction of a system, eliminate offsets and produce large initial changes.

4. Research Data and Results

The following is the *AVR* Parameter data derived from the manual book of the generator which is used as the object of research. In this research, the Sengkang sector generator will be used as a tested case.

Table 1. Generator excitation parameter data in the South Sulawesi system

No.	Generator	K_A (p.u)	T_A (Seconds)	*VA* max	*VA* min
1	PLTA Bakaru	400	0.04	0.71	-0.71
2	PLTA Teppo (Pinrang)	1	0.02	1	-1
3	PLTD Tallasa	1	0.02	1	-1
4	PLTD Suppa	1	0.02	1	-1
5	PLTU Barru	1	0.02	1	-1
6	PLTU Tallo	100	0.04	1	-1
7	PLTD Agreko (T Lama)	100	0.04	1	-1
8	PLTD Sungguminasa	10	0.02	18.3	-18.3
9	PLTU Arena (Jeneponto)	10	0.02	18.3	-18.3
10	PLTA POSO	400	0.04	0.71	-0.71
11	PLTA Tmanipi (Sinjai)	4	0.02	5.99	-5.99
12	PLTGU Sengkang	300	0.04	1	-1
13	PLTD Malea (Toraja)	10	0.02	18.3	-18.3
14	PLTD Palopo	4	0.02	5.99	-5.99
15	PLTA Bili-Bili	4	0.02	5.99	-5.99

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Table 2. Generator constant data on Sengkang Power Plant

Gain	Time Constant
$K_A = 400$	$T_A = 0.04$ *second*
$K_E = 1$	$T_E = 0.5$ *second*
$K_G = 1$	$T_G = 1$ *second*
$K_R = 1$	$T_R = 0.025$ *second*

From the *AVR* parameter data, if it is made in the form of a block *AVR* diagram will be:

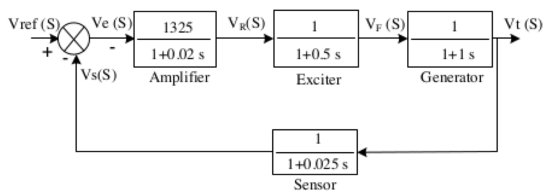

Figure 5. Block diagram of research results

where the K_A parameter value is variable, but the train constant used on the machine is now 1325. The simplified form of the *AVR* block diagram above is as follows:

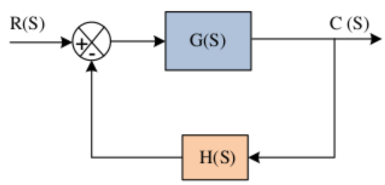

Figure 6. Simplification block diagram

so the equation for the function of the closed loop :

$$\frac{C\,(s)}{R(s)} = \frac{G(s)}{1+G\,(s)H\,(s)} \tag{5}$$

from the data obtained then made in the form of an open loop function G(s)H(s) to be

$$G(s)H(s) = \frac{K_A K_E K_G K_R}{(1+T_A s)(1+T_E s)(1+T_G s)(1+T_R s)}$$
$$G(s)H(s) = \frac{K_A.1.1.1}{(1+0.002\ s)(1+0.5\ s)(1+s)(1+0.025\ s)}$$

then the mathematical model simply becomes

$$G(s)H(s) = \frac{4000\ K_A}{S^4+93\ s^3+2272\ S^2+6180_s+4000} \tag{6}$$

the equation 6 is added with constant 1 (one) so that the system characteristic equation is obtained as follows:

$$1 + G(s)H(s) = 1 + \frac{4000\,K_A}{S^4 + 93\,S^3 + 2272\,S^2 + 6180\,s + 4000}$$

$$1 + G(S)H(S) = \frac{S^4 + 93\,S^3 + 2272\,S^2 + 6180\,s + 4000 + 4000\,K_A}{S^4 + 93\,S^3 + 2272\,S^2 + 6180\,s + 4000} \quad (7)$$

substitution Equation 7:

$$\frac{C(s)}{R(s)} = \frac{G\,(S)}{\frac{S^4 + 93\,S^3 + 2272\,S^2 + 6180\,s + 4000 + 4000\,K_A}{S^4 + 93\,S^3 + 2272\,S^2 + 6180\,s + 4000}}$$

$$= \frac{G(S)(S^4 + 93\,S^3 + 2272\,S^2 + 6180\,s + 400)}{S^4 + 93\,S^3 + 2272\,S^2 + 61800\,s + 4000 + 4000\,K_A}$$

According to the Routh stability criteria:

$$S^4 \quad +93\,S^2 + \quad 6180\,S + 4000 + 4000K_A = 0$$

$$\begin{array}{llll} S^4 & 1 & 2272 & 4000 + 400K_A \\ S^3 & 93 & 6180 & 0 \\ S^2 & A_1 & A_2 & \\ S^1 & B_1 & & \\ S^0 & C_1 & & \end{array}$$

where:

$$A_1 = \frac{(93x2272) - (1X6180)}{93} = 2205.548$$

$$A_2 = \frac{\left(93x(400 + 4000\,K_A)\right) - (1x0)}{93} = 4000 + 4000K_A$$

$$B_2 = \frac{(2205.548x6180) - (93x(4000 + 4000K_A))}{2205.548} = 6011.334 - 168.66\,K_A$$

$$C_1 = \frac{\left((6011.334 - 168.66\,K_A)X(4000 + 4000K_A)\right) - (2205.508x))}{(6011.334 - 168.66\,K_A)}$$

$$4000 + 4000K_A$$

To get a range of K_A values where the condition of a system is stable if column 1 is positive (> 0):

$B_1 = 6011.334 - 168.66\,K_A > 0$
$- 168.66\,K_A > - 6011.334$
$- K_A > - 35.642$
$K_A < 35.642$

and

$C_1 = 4000 + 4000\,K_A > 0$
$4000\,K_A > - 4000$
$K_A > - 1$

So the range of values for K_A:

$$-1 < K_A < 35.642$$

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From the results of calculations using the Routh stability criteria then the value is simulated using MATLAB as follows:

A. Without a *PID* controller

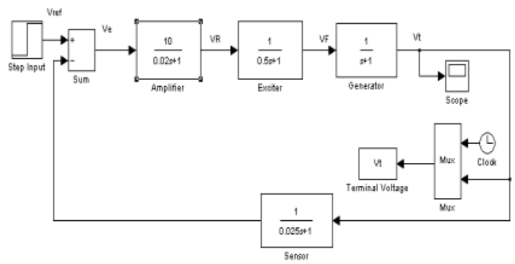

Figure 7. MATLAB Simulation Diagram Block without *PID* controller

For gain $K_A = 22$

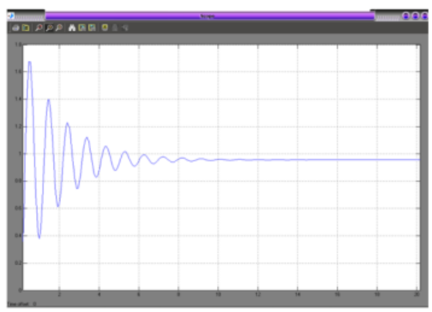

Figure 8. MATLAB simulation results for $K_A = 22$ without a *PID* controller

B. With a *PID* controller

Add the PID controller to the AVR simulation block diagram with the settings as shown below:

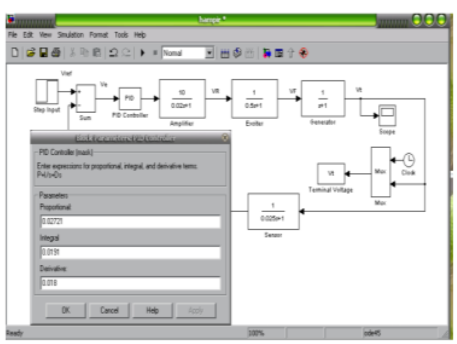

Figure 9. MATLAB simulation model with *PID* controller

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For $K_A = 22$

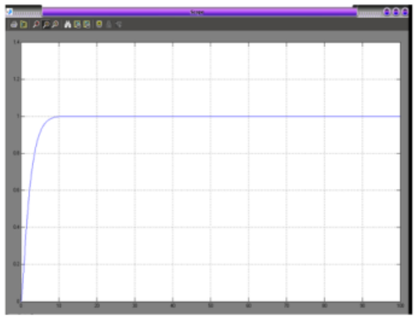

Figure 10. Simulation results for $K_A = 22$ with a *PID* controller

The simulation results obtained in the parameter settings $Kp = 0.0272$, $Ki = 0.0191$, and $Kd = 0.018$, in full as the following in Table 3:

Table 3. MATLAB simulation results

No	*KA* constant	No *PID* Control		With *PID* Control	
		Maximum overshoot (p.u)	Time (seconds)	Overshoot maksimum (p.u)	Time (seconds)
1	1	0.52	3.95	1	563.9
2	10	1.3	7.25	1	31.95
3	20	1.6	10.21	1	12.5
4	22	1.68	14.5	1	10.15
5	30	1.7	32.5	1.01	13.26
6	36	Stability is not achieved	Stability is not achieved	1.025	11.85
7	1325	Unable to run	Unable to run	1.2	8.9

Table 3 shows the simulation results without *PID* control and with *PID* control on generators in the Sengkang sector. By increasing the gain K_A value, it is seen that the overshoot and settling time values are getting bigger. For gain $K_A = 36$, for an uncontrolled AVR system, the *AVR* system is unstable. The next time the gain is increased again until it reaches $K_A = 1325$, the computational program will not converge so that the simulation cannot run. In contrast, when the *AVR* is mounted on the *PID* control, when the K_A gain = 36, the *AVR* is still stable with an output voltage having an overshoot of 1.025 per unit and a settling time of 11.85 seconds

5. Conclusions

Based on the research we have done, we can conclude the following:

1. Determination of the value of the amplifier constant (K_A) on an AVR (Automatic voltage Regulator) should refer to the value limit obtained from the calculation results with the *Routh* stability criteria method, which is in the range -1 <K_A <35,642. Giving the best amplifier constant (K_A) is the setting $K_A = 1$ (without the *PID* controller), where the setting is obtained the fastest stable time with the lowest level of oscillation (transient).
2. The addition of PID controllers (Proportional, Integral, and Derivative) will be able to reduce or even eliminate oscillations (transients) that occur in the generator with the right K_p, Ki, and Kd parameter

settings namely in the parameter settings $K_p = 0.0272$, $Ki = 0.0191$, and $Kd = 0.018$ with a K_A value of 22, where the setting does not experience the slightest transient and the fastest stable time.

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