Designing and Modeling of a Synchronous Generator Using AGC, PSS, and AVR Case Study on Tis Abay II Hydroelectric Power System

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Abstract. This paper explains the design, modeling, and control of a synchronous generator using Automatic Generation Control (AGC) and Power System Stabilizer (PSS) with a combination of Automatic Voltage Regulator (AVR) for a hydroelectric power system. In the proposed system the damping torque and another source of negative damping of the generator can be reduced by the AVR. A classical PID controller is used in the AVR system. Interconnecting (synchronizing) the generator in a tie system, the overall system fluctuation due to a large disturbance in one of the interconnections is mathematically analyzed and the transient & steady state performance of the controller are evaluated.

Generally the work intended in designing and modeling the controller for enhancement of power system stability with steady-state and transient analysis, the application to the sudden increase in power input, and the application of three-phase fault have been examined using Matlab/Simulink. The model is also used to simulate the performance of tie line system under the same phase faults as well as load disturbance conditions. Power system stabilizers designed to enhance the damping of power system oscillations.

The designed PSS and AGC improved the performance of power system dynamic stability. Besides, the desired frequency and power interchange with the neighboring system is maintained by the AGC. The total system generation against system load and losses could be balanced.

Keywords: Synchronous generator · Automatic Generation Control · Automatic Voltage Regulator

1 Introduction

The ability of power system to recover from faults is becoming more important nowadays because of the complexity of the system. Then, in the power system voltage and frequency should be maintained within narrow and rigid values, and In case of interconnected operation, the tie line power flows must be maintained at the specified values in practical applications because of generation must adequate to meet the load demand.

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The electric power system is often subjected to various disturbances, caused by, for example, fault activating, capacitor switching, large load changing, transmission line switching, etc. With appropriate operations on power system controls such as correct circuit breaker operations and proper generator excitation controls, the disturbing power system can either regain the pre-disturbance operating state or reach a new stable operating state after the disturbances [10].

The generator excitation system maintains the generator voltage and controls the reactive power flow. It is known that a change in the real power demand affects essentially the frequency, whereas a change in the reactive power affects mainly the voltage magnitude. The interaction between voltage and frequency controls is generally weak enough to justify their analysis separately. In this paper the reactive power control is achieved by manipulating the generator excitation system using PID controlled AVR. An increase in the reactive power load of the generator is accompanied by a drop in the terminal voltage magnitude. The voltage magnitude is sensed through a potential transformer on one phase. This voltage is rectified and compared to the DC setpoint signal. The amplified error signal controls the exciter field and increases the exciter terminal voltage. Thus, the generator field current is increased, which results in an increase in the generated emf. The reactive power generation is increased to a new equilibrium, raising the terminal voltage to the desired value.

The purposes of AGC are to maintain system frequency very close to a specified nominal value, to maintain the generation of individual units at the most economic value, to keep the correct value of tie-line power between different control areas. Automatic Generation Control (AGC) is define by IEEE as the regulation of the power output of electric generators within a prescribed area in response to changes in system frequency, tie line loading, or the regulation of these to each other, so as to maintain the scheduled system frequency and/or the established interchange with other areas within predetermined limits.

In addition, Automatic Generation Control (AGC) is a very important issue in power system operation and control for supplying sufficient and both good quality and reliable electric power. A sudden load change or disturbances in a single area or multi-area power system, the frequency and power undergo a fluctuation which persists for a very long time. This fluctuation is very poorly damped. Since these oscillations are the result of an imbalance of power. The generation is adjusted automatically by Automatic Generation Control to restore the frequency to the nominal value as the system load changes continuously [5].

2 Designing and Modeling of Controller

2.1 Automatic Voltage Control (AVR)

The main elements of AVR include excitation circuit, generator field, sensor and first order amplifier. Figure 1 below depicts the block diagram of AVR with PID controller.

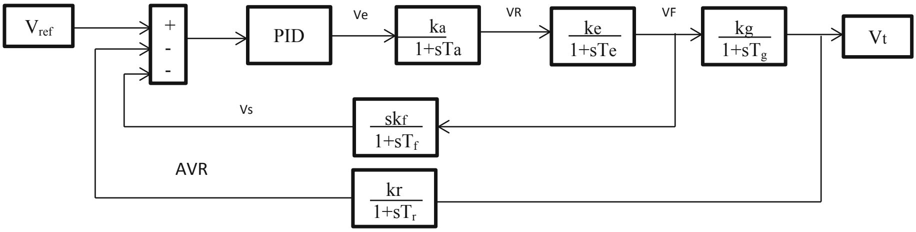

Fig. 1. Block diagram of AVR with PID and stabilizer

Equations (1) to (5) shows the mathematical model of amplifier, exciter, generator field, and PID respectively. The transfer function of first order amplifier is:

$$\frac{V_R(s)}{Ve(s)} = \frac{Ka}{1 + sTa} \tag{1}$$

Where: $Ka\ and\ Ta$ are the dc gain and time constant respectively.

The transfer function of the exciter circuit is also first order and it is given in Eq. (2) where Ke and Te are dc gain and time constant of the exciter,

$$\frac{V_F(s)}{V_R(s)} = \frac{Ke}{1 + sTe} \tag{2}$$

The transfer function relating the generator terminal voltage to its field voltage can be represented by a gain Kg and a time constant Tg is formulated as:

$$\frac{Vt(s)}{V_F(s)} = \frac{Kg}{1 + sTg} \tag{3}$$

A potential transformer used as feedback sensor is accompanied by bridge rectifier. It is modeled by a simple first-order transfer function given by:

$$\frac{Vs(s)}{Vt(s)} = \frac{Kr}{1 + sTr} \tag{4}$$

Where Kr sensor gain constant and Tr be Sensor time constant.

PID Control: Determination of the proportional, integral and derivative constants of the controller is called the tuning-in process. The transfer function of a PID controller can be written as:

$$G_{PID}(s) = K_p + \frac{K_i}{s} + K_d = \frac{K_d s^2 + K_p s + K_i}{s} \tag{5}$$

The value of K_p, K_d and K_i is obtained by matlab tuning method.

2.2 Automatic Generation Control (AGC)

The objective of AGC is to minimize the transient deviations and to provide zero steady-state errors of these variables in a very short time [2–5]. The AGC involves *Load Frequency Control (LFC)* to achieve real power balance by adjusting the turbine output and the *Supplementary loop* to maintain a zero frequency deviation. The block diagram of the AGC for a single power system is shown in Fig. 2 below.

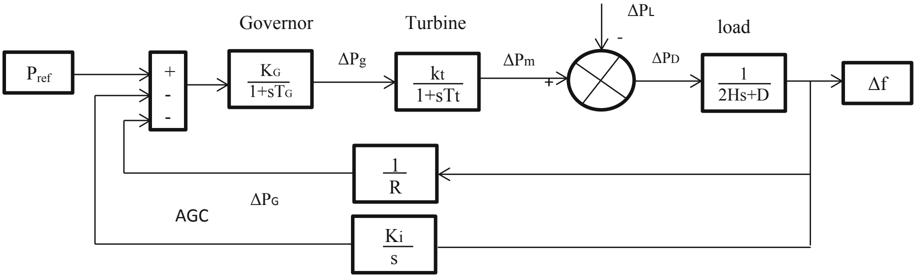

Fig. 2. Block diagram of AGC for a single power system

And a two area interconnected power system is shown in Fig. 3.

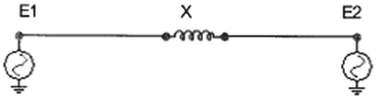

Fig. 3. Single line diagram of two area interconnected system

Tie line power flow from area 1 to area 2 can be written as:

$$P_{tie,12} = \frac{E_1 E_2}{X} sin(\delta_1 - \delta_2) \tag{6}$$

Where δ_1 and δ_2 are power angles.
Linearizing about an initial operating point we have

$$\Delta P_{tie,12} = T_{12} \Delta \delta_{12} = T_{12}(\delta_1 - \delta_2) \tag{7}$$

Where,

$$T_{12} = \frac{|E_1||E_2|}{P_{r1} X} \cos(\delta_1 - \delta_2) = \text{Synchronizing coefficient} \tag{8}$$

$$\Delta P_{tie,12} = 2\pi T_{12}(\Delta f_1 - \Delta f_2) \tag{9}$$

And Tie line power flow from area 2 to area 1 can be written as:

$$\Delta P_{tie,21} = 2\pi T_{21}(\Delta f_2 - \Delta f_1) \tag{10}$$

Where

$$T_{21} = \frac{|E_1||E_2|}{P_{r2}X}\cos(\delta_2 - \delta_1) = \text{Synchronizing coefficient} \tag{11}$$

Then from the above equation:

$$\Delta P_{tie,21} = a_{12}\Delta P_{tie,12} \tag{12}$$

Where,

$$a_{12} = \frac{-P_{r1}}{P_{r2}} \tag{13}$$

That is $\Delta f = \Delta f1 = \Delta f2$. Thus, for area 1, we have

$$\Delta P_{m1} - \Delta P_{D1} - \Delta P_{12} = D_1\Delta f \tag{14}$$

Where, ΔP_{12} is the tie-line power flow from Area 1 to Area 2, and for Area 2:

$$\Delta P_{m2} + \Delta P_{12} = D_2\Delta f \tag{15}$$

The mechanical power depends on regulation. Hence

$$\Delta P_{m1} = -\frac{\Delta f}{R_1} \quad \text{And} \quad \Delta P_{m2} = -\frac{\Delta f}{R_2} \tag{16}$$

Substituting these equations, yields

$$\left(\frac{1}{R_1} + D_1\right)\Delta f = -\Delta P_{12} - \Delta P_{D1} \quad \text{And} \quad \left(\frac{1}{R_2} + D_2\right)\Delta f = \Delta P_{12} \tag{17}$$

Solving for Δf, we get

$$\Delta f = \frac{-\Delta P_{D1}}{\left(\frac{1}{R_1} + D1\right) + \left(\frac{1}{R_2} + D2\right)} = \frac{-\Delta P_{D1}}{\beta_1 + \beta_2} \tag{18}$$

$$and \qquad \Delta P_{12} = \frac{-\Delta P_{D1}\beta_2}{\beta_1 + \beta_2} \tag{19}$$

Where $\beta_1 = (D_1 + 1/R_1)$ and $\beta_2 = (D_2 + 1/R_2)$.

The area controls error (ACE) is met when the control action maintains frequency at the scheduled value and net interchange power (tie-line flow) with neighboring areas at the scheduled values.

The ACE of the two areas are given by

$$\text{For area 1}: \quad \text{ACE}_1 = \Delta P_{12} + \beta_1 \Delta f \qquad \text{For area 2}: \quad \text{ACE}_2 = \Delta P_{12} + \beta_1 \Delta f \tag{20}$$

The overall block diagram of when two areas interconnected with AGC and HTG as shown below figures (Fig. 4):

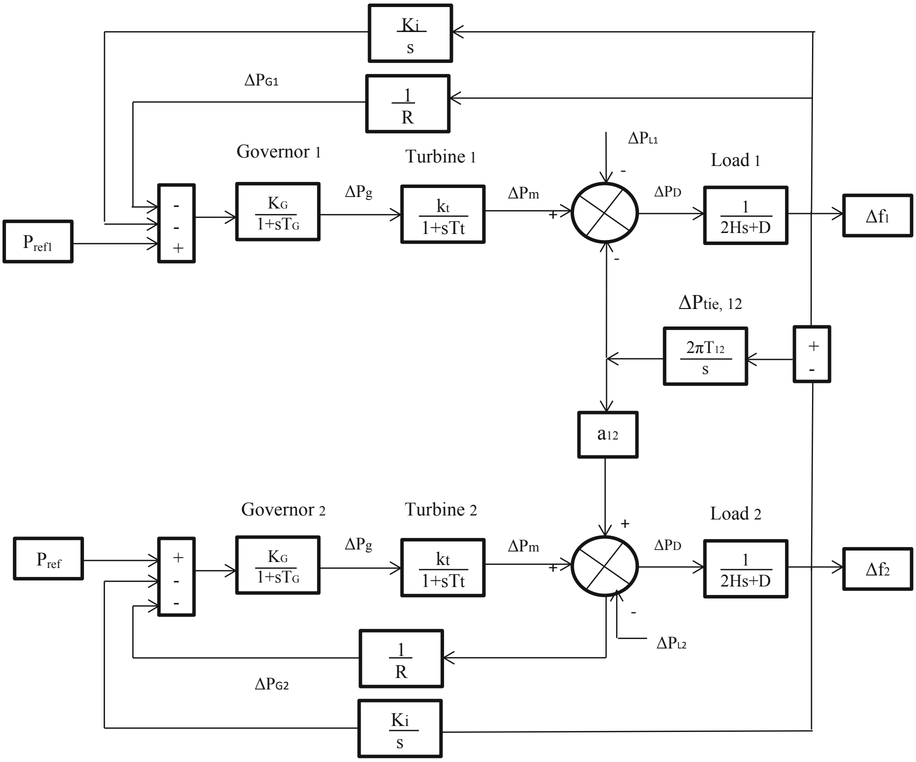

Fig. 4. Block diagram of AGC for two-area operation

2.3 AGC with AVR and PSS

The interaction between voltage and frequency controls is generally weak enough to justify their analysis separately. The methods of improving the voltage profile in the electric systems are transformer load tap changers, switched capacitors, step voltage regulators and static var control equipment. The controller of voltage or reactive power of generator is excitation control using the automatic voltage regulator (AVR). The main objective of an AVR is to hold the terminal voltage magnitude of a synchronous generator at a desired value [6]. This e.m.f determines the magnitude of real power and hence the AVR loop felt in the AGC loop. When we include the small effect of voltage on real power, we get the following equation:

$$\Delta P_e = P_s \Delta\delta + K_2 E' \tag{21}$$

Where, $K_2 = \frac{\Delta P_e}{E'}\, with\, constant\, \Delta\delta$ = is load angle, and $P_s = \frac{\Delta P_e}{\Delta\delta}\, with\, constant\, E'$ is synchronizing power coefficient.

Generally, all the variables with subscript 0 are values of variables evaluated at their pre-disturbance steady-state operating point from the known values of P_0, Q_0, and V_{t0}.

$$i_{q0} = \frac{P_0 V_{to}}{\sqrt{(P_0 x_q)^2 + (V_{t0}^2 + Q_0 x_q)^2}} \qquad v_{d0} = i_{q0} x_q \tag{22}$$

$$v_{qo} = \sqrt{V_{t0}^2 - v_{t0}^2} \qquad i_{d0} = \frac{Q_0 + x_q i_{q0}^2}{v_{q0}} \tag{23}$$

$$E_{q0} = v_{q0} + i_{d0} x_q \qquad E_0 = \sqrt{(v_{d0} + x_e i_{q0})^2 + (v_{q0} - x_e i_{d0})^2} \tag{24}$$

$$\delta_0 = \tan^{-1}\frac{(v_{d0} + x_e i_{q0})}{(v_{q0} - x_e i_{d0})} \qquad K_1 = \frac{x_q - x_d'}{x_e + x_d'} i_{q0} E_0 \sin\delta_0 + \frac{E_{q0} E_0 \cos\delta_0}{x_e + x_q} \tag{25}$$

$$K2 = \frac{E_0 \sin\delta_0}{x_e + x_d'} \qquad K3 = \frac{x_d' + x_e}{x_d + x_e}, \qquad K4 = \frac{x_q - x_d'}{x_e + x_d'} E_0 \sin\delta_0 \tag{26}$$

$$K5 = \frac{x_q}{x_e + x_q}\frac{v_{d0}}{V_{t0}} E_0 \cos\delta_0 - \frac{xd'}{x_e + x_d'}\frac{v_{q0}}{V_{t0}} E_0 \sin\delta_0 \qquad K6 = \frac{x_e}{x_e + x_d'}\frac{v_{q0}}{V_{t0}} \tag{27}$$

By including the small effect of rotor angle upon generator terminal voltage, we may write

$$\Delta V_t = K_5 \Delta\delta + K_6 E' \tag{28}$$

Where K_5 is changed in terminal voltage for a small change in rotor angle at constant stator e.m.f and K_6 is a change in terminal voltage for a small change in stator e.m.f at constant rotor angle. Finally, modifying the generator field transfer function to include the effect of rotor angle, we may express the stator e.m.f as

$$E' = \frac{K_g}{1 + T_g}\left(V_f - K_4 \Delta\delta\right) \tag{29}$$

The constants K_1, K_2, K_3, K_4, and K_6 are usually positive; however, K_5 may take either positive or negative value depending on the impedance $R_E + jX_E$.

The overall block diagram of AGC, AVR, and stabilizer is (Fig. 5):

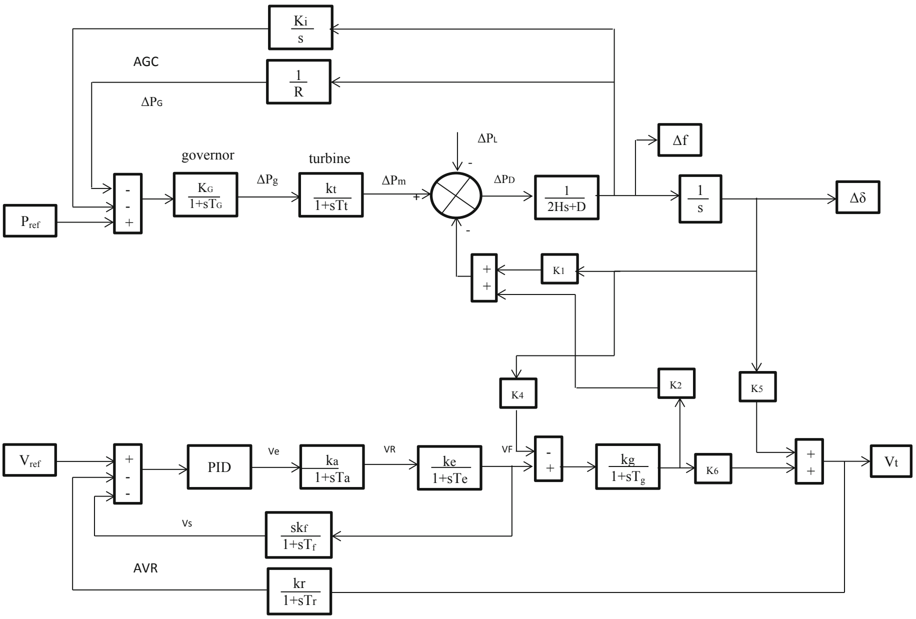

Fig. 5. Block diagram of AGC and PSS with AVR

3 Simulation Results and Discussion

While doing this paper, we have two conditions to run Tis Abay II hydroelectric power system these are at:

1. Steady-state condition
2. Fault condition

The following operating conditions for a synchronous machine connected to an infinite bus through a transmission line of the Tis Abay II hydroelectric power system (Tables 1 and 2).

Table 1. Nameplate rating data of generator

Rating data for generator	Type
Manufacture	Kvaerner hangar
Rated capacity (S)	40 MVA
Rated power (S)	36.8 MW
Rated voltage (V_{LL})	13.8 kV
Rated current (I_L)	2.1994 kA
No of phase, power factor (cos Φ)	0.9
Rated speed	214.3 rpm
Runaway speed	428 rpm
Rated frequency	50 Hz
Direction of rotation	Clockwise viewed from above
Insulation class	F
Type of excitation	Static SCR

Table 2. Parameter of AVR and exciter

Elements	Parameters	Data for simulation
Amplifier	Regulator gain Ka	10–400
	Regulator amplifier time constant Ta(s)	0.02 s
Exciter	Exciter constant related to self-excited field Ke	1
	Exciter time constant Te(s)	0.5 s
Feedback stabilizer	Generating stabilizing circuit gain K_F	0.03
	Regulator stabilizing The time constant T_F(s)	1
Generator	Generator terminal voltage to its field voltage K_g	1
	Generator time constant T_g(s)	2 s
Sensor (Low-pass filter)	Gain (K_R)	1
	Time constant (T_R)	0.05 s

3.1 System Running at Steady State Condition

A. ***The synchronous generator block diagram with AVR, FS and PID controller shown below:***
See Fig. 6.

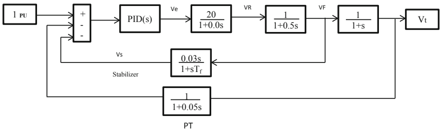

Fig. 6. Block diagram of SG with AVR and PID

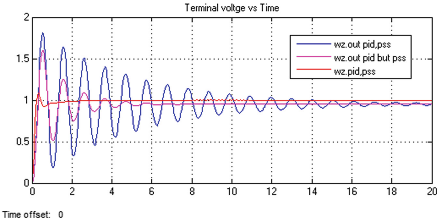

Fig. 7. Terminal voltage response

Result and Discussion 1:
From the simulation result in Fig. 7 the generator shows

i. With only AVR the terminal voltage is not controlled to the desired value (1 Pu = 13.8 kV) which is 0.9 Pu (12.42 kV) after almost 8 s and also the overshot value is 1.8 Pu.
ii. With AVR and stabilizer the oscillation is decreased (1.6 Pu) and the settling time is decreased which is 4 s and the overshoot values are 1.2 Pu but it does not reduce the steady-state error.
iii. With AVR, stabilizer and PID the terminal voltage is controlled which is the settling time, overshoot and steady-state errors are almost zero.

B. ***The complete block diagram of the AGC model and its simulation of an isolated power system***:
See Figs. 8 and 9.

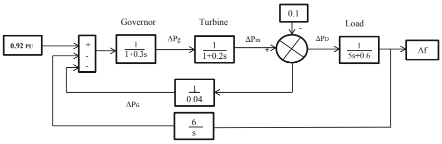

Fig. 8. Block diagram of AGC

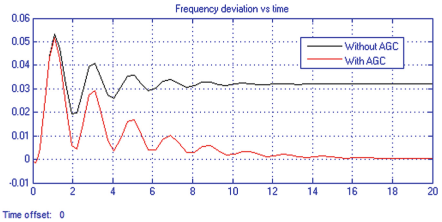

Fig. 9. Frequency deviation response

Result and Discussion 2:

i. With only LFC the frequency deviation (change) is not controlled to the desired value (0 Pu = 50 Hz) that is 0.03 Pu (1.5 Hz) have an error after almost 8 s and the overshot value is 0.056 Pu.
ii. However, LFC with supplementary that means with AGC is controlled which is the steady-state error is zero Pu (new frequency = 50 Hz) after 10 s and the overshoot is decreased by almost 0.05 Pu.

C. ***The block diagram and its simulation of AGC Including AVR and Stabilizer***
See Figs. 10.

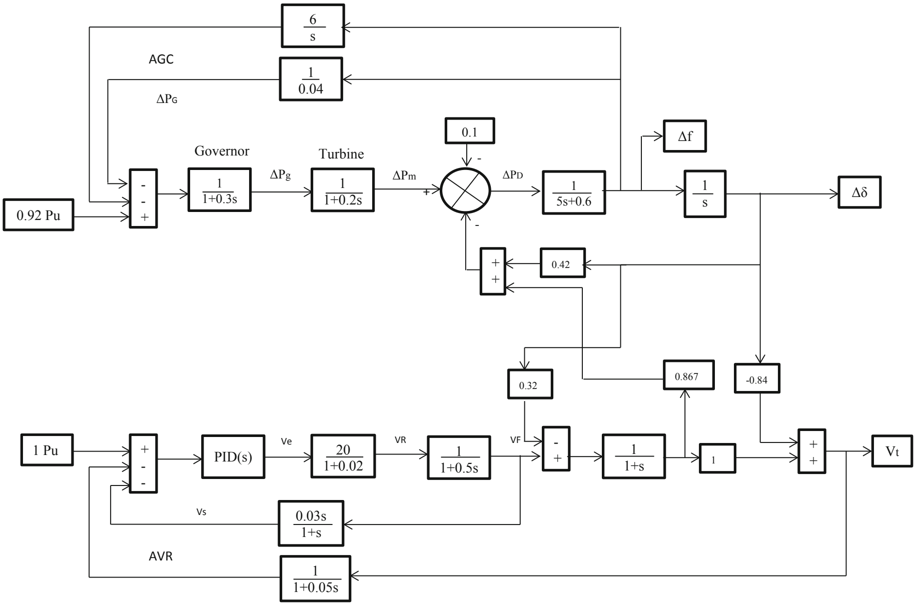

Fig. 10. Matlab/Simulink block diagram of AGC and PSS with AVR

Simulation Results:

See Figs. 11 and 12.

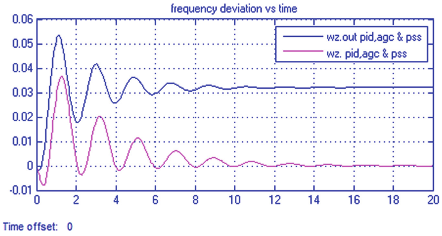

Fig. 11. Frequency deviation response

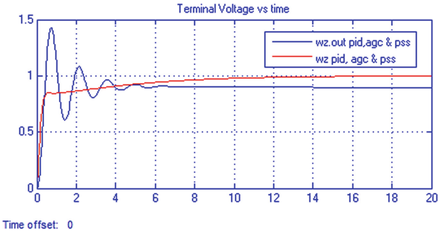

Fig. 12. Terminal voltage response

Result and Discussion 3:

a. With only LFC the frequency deviation (change) is not controlled to the desired value (0 Pu = 50 Hz) that is 0.03 Pu (1.5 Hz) have an error after almost 8 s and also the overshot value is 0.056 Pu.
b. However, LFC with supplementary that means with AGC is controlled which is the steady-state error is zero Pu (new frequency = 50 Hz) after 10 s and the overshoot is decreased by almost 0.05 Pu (Fig. 14).
c. With only AVR the terminal voltage is not controlled to the desired value (1 Pu = 13.8 kV) which is 0.9 Pu (12.42 kV) after almost 8 s. and also the overshot value is 1.8 Pu (Fig. 15).

d. With AVR and stabilizer the oscillation is decreased (1.6 Pu) and the settling time is decreased which is 4 s and the overshoot values are 1.2 Pu but it does not reduce the steady-state error.
e. With AVR, stabilizer and PID the terminal voltage is controlled which is the settling time, overshoot and steady-state errors are almost zero (Fig. 15).

Note: Therefore, the Automatic generation controller is controlled or maintained the frequency from the equation if the frequency is controlled the output power; the rotor angle and speed are controlled. In addition, the automatic voltage controller with PID will be controlled the terminal voltage also the reactive power.

D. ***The block diagram and its simulation of the two areas interconnected***
See Fig. 13.

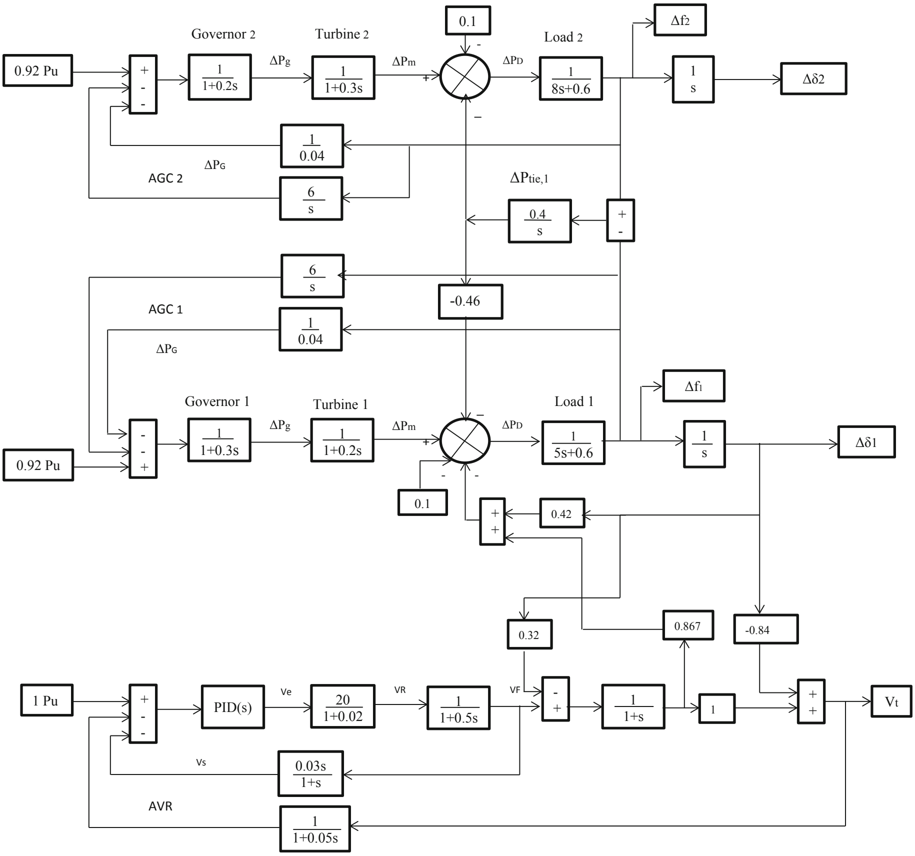

Fig. 13. Block diagram of two areas interconnected system with AVR and AGC

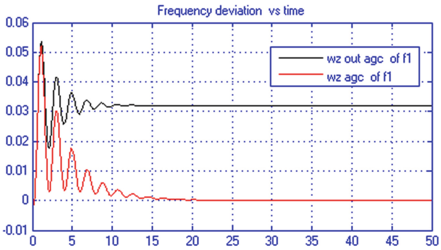

Fig. 14. Frequency deviation response

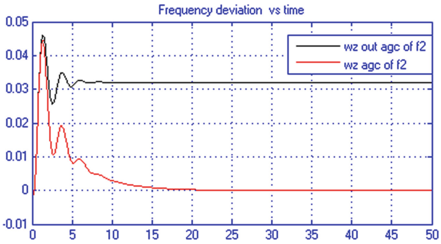

Fig. 15. Frequency deviation response

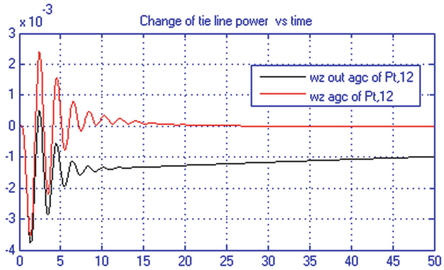

Fig. 16. Tie line power response

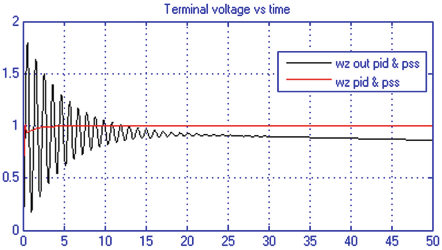

Fig. 17. Terminal voltage response

Simulation Results:
Result and Discussion 4:
From the simulation result in Figs. 14, 15, 16 and 17 the generator shows

i. With only LFC the frequency deviation (change) of both power systems one and two are not controlled to the desired value (0 Pu = 50 Hz) that is 0.032 Pu (1.6 Hz) have an error after almost 8 s but with AGC the steady-state will be eliminated after almost 10 s (Figs. 17 and 18).
ii. From Fig. 16 the tie-line power without AGC (only LFC) have error (unstable state) but with AGC, it will be stable and decrease the steady state error almost eliminated after almost 15 s.
iii. In addition, from Fig. 17 AVR, with PID the terminal voltage is controlled which is the settling time, overshoot and steady state errors are almost zero.

3.2 Simulation Result of the System with Fault

E. ***The block diagram and its simulation of AGC Including AVR and PSS with fault***:

Let, the fault (pulse generator) is occurred at t = 15 s is occurred on the input and the fault duration is 250 ms.

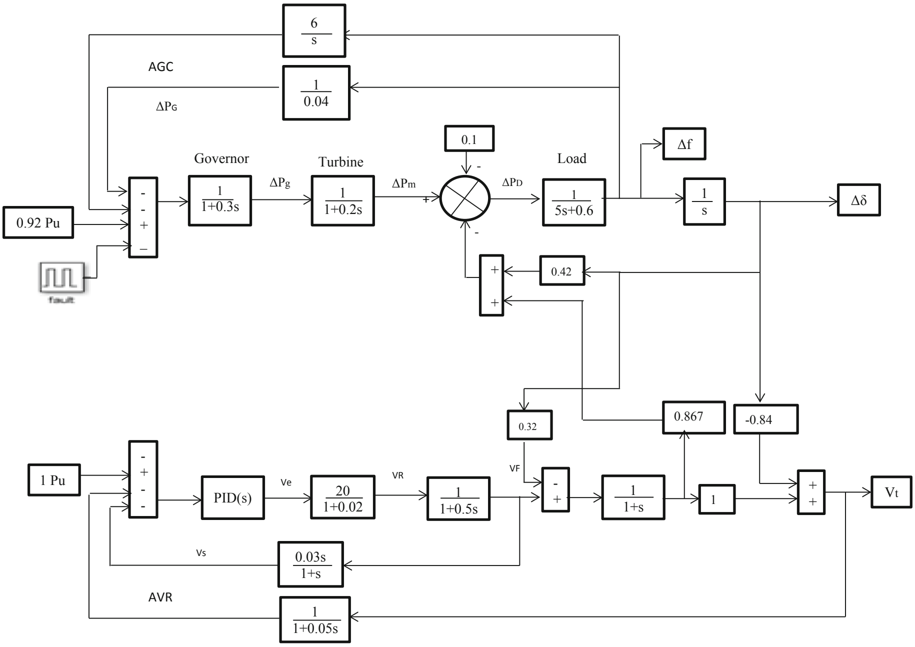

Fig. 18. Block diagram of SG including AGC and AVR with fault

Simulation Results:
Result and Discussion 5:

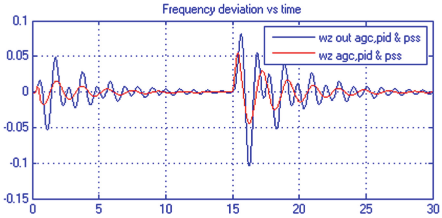

Fig. 19. Frequency deviation response with fault

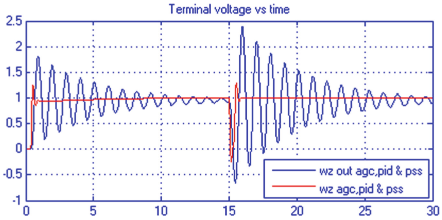

Fig. 20. Terminal voltage response with fault

In the above Figs. 19, 20 when the fault occurs at 15 s in the power system it will be cleared quickly (fault duration time is 0.25 s) and became at normal value with and without a controller.

4 Conclusion

Based on the simulation result, it is possible to conclude that:

- This paper focuses on the improvement of power system stability in the power system by connecting a synchronous generator to the controller.
- Due to the connection of AGC and PSS in the grid, it is seen that the change of frequency (error), and output power are achieved at the nominal or desired value and decreasing the oscillation.
- When there is sudden load change in a single synchronous generator (power system) or any interconnected area, the frequency and tie-line power are affected. It is essential to minimize these errors for economic and reliable operation of the power system. Therefore, the AGC designed here to meet the stated demand.
- AGC Controller designed here minimizes the change in frequency in the single power system area as well as in multi-area.
- AVR with PID and PSS, it is seen that the terminal voltage as well as the reactive power also controlled and is achieved at the nominal or desired value and damping the oscillation of the system.

Acronyms

B: Frequency Bias factor
D: Percent change in load divided by the percent change in frequency
Ki: Supplementary control constant
H: Inertia Constant
ΔP: Change in power
ΔP_m: Change in mechanical power input
ΔP_D: Change in power demanded by the load
ΔP_{tie}: Tie-line power deviations
ΔP_V: Change in valve position from nominal
R: Speed Droop Characteristic
Tg: Speed governor time constant
Tt: Turbine time constant
f: Frequency of system
Δf: Change in system frequency

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