Effects of the Droop Speed Governor and Automatic Generation Control AGC on Generator Load Sharing of Power System

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Article Info

Article history:

Received Mei 12, 2015
Revised Jun 20, 2015
Accepted Jul 26, 2015

Keyword:

Automatic Generation Control
Frequency control
Power control
Power quality
Power system interconnection

ABSTRACT

In power system, as any inequality between production and consumption results in an instantaneous change in frequency from nominal, frequency should be always monitored and controlled. Traditionally, frequency regulation is provided by varying the power output of generators which have restricted ramp rates. The Automatic Generation Control AGC process performs the task of adjusting system generation to meet the load demand and of regulating the large system frequency changes. A result of the mismatches between system load and system generation, system frequency and the desired value of 50 Hz is the accumulation of time error. How equilibrium system frequency is calculated if load parameters are frequency dependent, and how can frequency be controlled. Also, how do parameters of a speed governor affect generated power. The transient processes before system frequency settles down to steady state. Finally, AGC in what way is it different from governor action. This paper presents new approaches for AGC of power system including two areas having one steam turbines and one hydro turbine tied together through power lines.

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1. INTRODUCTION

In general, electrical power systems are interconnected to provide secure and economical operation. The interconnection is typically divided into coalmen, with each consisting of one or more power utility companies [l]-[4]. The control areas are connected by transmission lines commonly referred to as tie-lines and the power flowing between control areas is called tie-line interchange power. One of the main responsibilities of each control area is to supply sufficient generation to meet the load demand of its customers, either with its own generation sources or with power purchased from other control areas. The speed-governing system provides a primary control function that responds quickly to frequency changes caused by a change in the active power balance between generation and load. For governs with speed-droop characteristics, a steady-state frequency deviation from the desired system frequency remains following the primary control action. This deviation is corrected using the AGC function. Compared to the primary control process, this control is slower to respond to changes in the load demand. AGC has been utilized by power utilities for several decades. The approach used today generality provides acceptable levels of performance based primary upon AGC operation criteria specified by the North American Electric Reliability Council (NERC) [5]-[9].

AGC is an important problem in power system operation and control, whenever a small load perturbation occurs, it causes the changes in tie-line power flow and frequency deviation. Many investigations in the area of AGC of interconnected power systems have been carried out in the past [10]-[13] and number of control strategies have been proposed to improve the performance of AGC. Present AGC schemes used to combat this problem utilize a static, linear system response characteristic to mode1 the actual variable, non-linear system response to frequency deviations. For interconnected power systems, the AGC control signal is determined from the sum of the tie-line power interchange between interconnected systems and the system frequency deviation weighted by a bias factor, which is the system response characteristic approximation. For an isolated power system, such as the NLH system, the control signal relies entirely on the weighted frequency deviation. Thus the approximation of the SRC becomes increasingly important in the AGC process of an isolated power system. Maintaining power system frequency at constant value is very important for the health of the power generating equipment and the utilization equipment at the customer end. The job of automatic frequency regulation is achieved by governing systems of individual turbine-generators and AGC or Load frequency control LFC system of the power system [14]-[20].

Direct speed governing and the supplemental adjustment of speed governor set points are the methods used on present day power systems for matching generation to load, for the allocation of generation output among generation sources, and for the achievement of desired system frequency. This tutorial provides the reader with basic information on speed governors and their application for system control. All speed governors, whether mechanical-hydraulic, electrohydraulic, or digital electro-hydraulic, have similar steady-state speed-output characteristics, so their application for system control (for slow changes) is the same. A large frequency deviation can have undesirable effects on power system like damaging equipment, degrading load performance, causing the transmission lines to be overloaded, interfering with system protection schemes and eventually, leading to an unstable condition for the power system. Thus, controlling frequency is an essential task for the power system operator. For keeping the frequency of a power system within a required range, the generation and demand should be kept in balance. In spite of considerable effort for forecasting electricity demand, making a completely accurate prediction is impossible. Second-to-second and minute-to-minute fluctuations are very difficult to foresee, which may result in a difference between load and dispatched generation [21]-[28].

Faster ramping results in more accurate response to the AGC signal and avoids overshooting. On the other hand, ramping too slowly may cause the resource to work against the needs of the system and impose the need to commit additional regulation resources. As the current compensation method, which is solely based on the capacity reserved for regulation, does not acknowledge the greater amount of frequency regulation service being provided by faster-ramping resources [29]-[33], FERC order forced all RTOs and ISOs to have a two level payments based on capacity and performance which have to consider the accuracy in following the AGC dispatch signal. Before deciding to have any additional payment to faster ramping resources because of their performance and accuracy, we should investigate to see if there is any adverse effect of very fast response to frequency fluctuations. Based on these effects we can decide about the real value of these resources. In this paper, we studied these effects by modeling the dynamic behavior of power system. The rest of the paper is organized as follow. Section 2 describes the economic dispatch and limitations of prime mover systems. Section 3 introduced a frequency and speed governor control model. Section 4 introduced AGC model. Simulations results will be discussed in section 5, and the conclusion is presented in section 6.

2. RESEARCH METHOD

The change in generation in steady state after a load change (due to governor and AGC action), may not be the most optimal one from an economic standpoint. Note that different generators may have different cost of generating power. A power plant or system operator may wish to re-adjust the generated power in various units for maximum economic benefit. This adjustment of generation is generally done manually and is often called "tertiary control". Of course, how this re-adjustment is done is dependent on generation cost, power –pricing mechanism and the ownership of generation. Interestingly, if power pricing itself is made a function of frequency, then tertiary control also may contribute to (slow) frequency control. This idea (called Availability Based Tariff) is implemented in some regions of our country [34]. Generation reserves available for control of frequency are typically only a fraction of the existing generation. Moreover, there are practical constraints like limits on the rate of rise of prime mover power (in a steam turbine) to avoid rapid heating. While an initial sudden change of about 10% can be tolerated, subsequently, rate of rise is limited to 2% (of plant MW rating) per minute. The boiler in a steam prime mover is relatively slow in maintaining the steam pressure by increasing fuel input. Thus as control valves open, restoration of steam pressure is slow. For some types of hydro turbines, there are forbidden operating zones due to cavitation effects in turbines. In countries like ours, where substantial generation shortage exists, load shedding may be done to keep frequency within bounds. In a two-area system, if governors are present on some machines in both areas power flow in certain ac line, which connects two areas is to be regulated, and frequency has to be brought back to its nominal value after any load generation change then the references of at least two governors (one in each area) in the system should be changed to achieve these objectives [35].

3. FREQUENCY AND SPEED GOVERNOR CONTROL:

In a previous works that frequency deviation can be quite substantial more than 3.0Hz for 10% change in load. In fact this deviation is considered unacceptably large (at this frequency, the generators will trip due to over-speeding) [36]. Therefore, depending on the frequency dependence of load, which is quite weak to bring about load generation balance is not a good operating practice. Therefore it is important to introduce frequency dependence of generated power. This is done by a speed control mechanism known as speed governing. Speed dependence can be introduced by having a feedback control system as shown in the Figure (1). A schematic is oversimplified, especially in the case of thermal/nuclear reactors, which have a more complicated control structure involving a boiler and reactor [37]. These additional controllers regulate other parameters like steam pressure by control of fuel, air and feed water. Therefore, strictly speaking, output power for steam turbines is not a function of control valve position alone. However, we shall use this simplified model to illustrate the concepts of speed control.

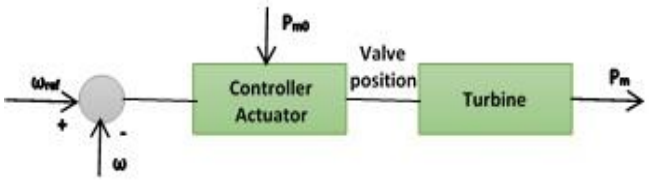


Figure 1. Speed governing feedback control system

The exact nature of generator power frequency steady state relationship can be set by the controller parameters and Pm0 the initial setting. Typically, in steady state, the generated output power in per unit is related to change of speed by the following relationship:

$$P_m = P_{m0} - k_G\left(\frac{f-f_{ref}}{f_0}\right) = P_{m0} - k_G\left(\frac{\omega-\omega_{ref}}{\omega_0}\right) \quad (1)$$

Where: f_0 is the rated frequency in Hz, ω represents the angular electrical speed in rad/s, and k_G is the per unit change in power for per unit change in frequency. If the base value of power is taken to be the generator rated active power, then reciprocal of k_G is also known as the droop. P_{m0} is the output when $f\text{-}f_{ref}=0$. k_G, P_{m0} and f_{ref} equivalent ω_{ref} can be set by system/plant operators. Normally k_G is set after proper co-ordination among various generators. It is not usually tinkered with during operation. However, P_{m0} and f_{ref} are adjusted by system operators or by slow acting automatic controllers to make change in generated power. We have seen the effect of speed droop settings on sharing of excess load between generators in steady state. Although we have considered only the steady state conditions, it is to be noted that governors, turbines and generators (and practically all constituents of a power system) are governed by dynamic equations. This means that steady state is not reached instantaneously. Indeed, if the transient processes are not stable, the system will not settle down to the steady state. Thus it is important to consider the dynamical equations which govern the physical structures, especially the prime mover system. While dynamical modelling of components is beyond the scope of this studied, we will briefly discuss the working of a steam governor. A speed governor is a device which senses speed deviation from its reference value and appropriately changes control valve position in a steam turbine or gate position in a hydraulic turbine. This is achieved in older units using mechanical and hydraulic arrangements (mechanical hydraulic governors), while in modern units, the sensing and computing functions are done electrically (electrohydraulic governors). A speed governor should allow us to change the governor gain and also change the speed and/or load reference. A governor may also have additional parameters which tailor its dynamic response so that instability does not take place. We study the frequency transients for a simplified two generator system with speed governing, by a studied system consider two identical generators supplying two loads as shown in the Figure (2).

The generator field voltage is controlled to maintain its terminal voltage. A simplified model of generator is used a voltage source behind an equivalent reactance x_g. The load are voltage dependent but not frequency dependent, and are of unity power factor, and V_0=1.0pu.

$$P_{L1} = 0.5\left(\frac{V_1}{V_0}\right)^2, \text{ and } P_{L2} = 0.5\left(\frac{V_2}{V_0}\right)^2$$

(2)

A simplified composite transfer function of governor and turbine for both generators and all values are on a common base as follows:

$$\Delta P_{mi} = C_{Gi}\left(\frac{0.2s+1}{0.7s+1}\right)\left(\frac{\omega_{ref}-\omega_i}{\omega_0}\right), \tag{3}$$

and $$P_{mi} = P_{m0i} + \Delta P_{mi}$$

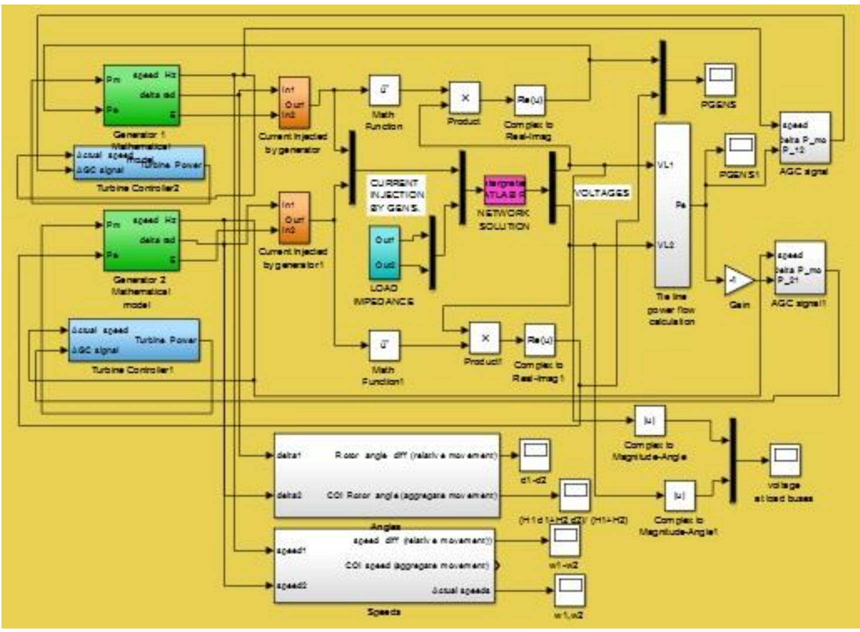


Figure 2. Two area studied system model

Assume that for both generators, Pm0i=0.5 and C_{Gi}=20, $\omega_{refi}=\omega_0=2\pi\times50$. Here, C_{Gi} represents the gain of a proportional speed controller. Note that in steady state:

$$\Delta P_{mi} = C_{Gi}\left(\frac{\omega_{refi}-\omega_i}{\omega_0}\right) \tag{4}$$

Thus C_{Gi} is related to the drop of the generator characteristic. The variation in generator speeds if load #1 is increased by 10%.

$$P'_{L1} = 0.55\left(\frac{V_1}{V_0}\right)^2 \tag{5}$$

Assume inertia constant of each generator H=3MJ/MVA, x_g=0.5, x_e=0.2, R=0.02, X=0.2. Initially the voltage at the load buses #1 and #2 are 1.0 pu. The natural transients associated with the electrical network/loads are assumed to be fast compared to the electro-mechanical transients; therefore the network and loads are represented by their sinusoidal steady state equations. The variation in generator speeds can be obtained by numerically integrating the swing equations and the dynamical equations corresponding to the speed governors and turbines. They are:

$$\frac{d(\omega_i-\omega_0)}{dt} = \frac{\omega_B}{2H_i}(P_{mi} - P_{ei}) = \frac{\omega_B}{2H_i}(P_{m0i} + \Delta P_{mi} - P_{ei}) \tag{6}$$

$$\frac{d\delta_i}{dt} = (\omega_i - \omega_0) \tag{7}$$

The dynamical equations of the turbine governor for each generator can be written as follows:

$$\frac{d\Delta P_{si}}{dt} = \frac{1}{0.7}\left(-\Delta P_{si} + C_{Gi}\left(\frac{\omega_{refi}-\omega_0}{\omega_0}\right)\right) \tag{8}$$

$$\Delta P_{mi} = C_{Gi}\left(\frac{\omega_{refi}-\omega_0}{\omega_0}\right) \times \frac{0.2}{0.7} + \Delta P_{si}\left(1 - \frac{0.2}{0.7}\right) \tag{9}$$

Where: ΔP_{si} is a state of the system. Verify that these yield the transfer function:

$$\Delta P_{mi} = C_{Gi}\left(\frac{0.2s+1}{0.7s+1}\right)\left(\frac{\omega_{refi}-\omega_i}{\omega_0}\right) \tag{10}$$

and $P_{ei} = Re(\bar{V}_{Gi}\bar{I}_{Gi}^*)$

Where $\bar{V}_{Gi}$ and $\bar{I}_{Gi}$ are the generator terminal voltages and current respectively. These may be obtained by solving the network in terms of δ_1 and δ_2. The initial conditions of the various state are as follows: Initial Conditions:

$$\Delta P_{si} = \Delta P_{mi} = \frac{\omega_{refi}-\omega_i}{\omega_0} = 0 \tag{11}$$

There is no power flow initially on the line connecting bus #1 and #2. Thus θ_1=θ_2 initially. If the initial phase angle at load bus #1 is taken to be zero, then θ_1=θ_2=0.0. δ_1=19.29^o, δ_2=19.29^o. verify that E_1=E_2=1.0595, so that the load bus voltages are 1.0 pu.

4. AUTOMATIC GENERATION CONTROL AGC:

We saw the load sharing in a multi-generator power system can be achieved using droop characteristics of governors. The sharing according to droop is irrespective of load location. However if non-zero governor droops are used a steady state frequency error will remain which needs to be corrected. Moreover, since all the governors respond to the load change irrespective of load location, there may be undesirable exchange of power between different areas of the grid. This is manifested as a change in the flows of lines interconnecting these areas. To ensure that frequency steady state error is corrected and generators in a particular area take on the burden of their own load, the load reference Pm0 of governors is adjusted slowly. This control is also called secondary control. This correction may be done over several minutes as opposed to 5-10 seconds for initial or primary control action of governors. Thus, while primary control (governor action) ensures that a large and sudden frequency fall or rise is prevented, secondary control or AGC ensures that frequency is brought back to the nominal value and inter-area power flow is regulated. Any change of reference value will lead to a change in sharing among the generators. Thus by slowly changing the reference of speed governors we can over-ride the sharing which is imposed by the droop characteristics, and which generators should change their governor references and what the exact value of these changes.

It is not feasible to independently change more than one governor reference in one area, otherwise there is no unique value of reference change for different governors. Thus if more than one governors in an area are on AGC, then their actions have to be in a pre-decided proportion and not independent of one another. The AGC concept is illustrated by the following schematic in the Figure 3. Each generator which has a governor can be represented as follows. The value of the load reference Pm0 is adjusted by AGC. The following Figure 4 shows how a generator in each area in a two area system receives feedback from a tie line P_{12}. The feedback is combined with the speed deviation signal in a certain proportion decided by the constant B. It is then fed to an integral controller, the output of which changes P_{m0}.

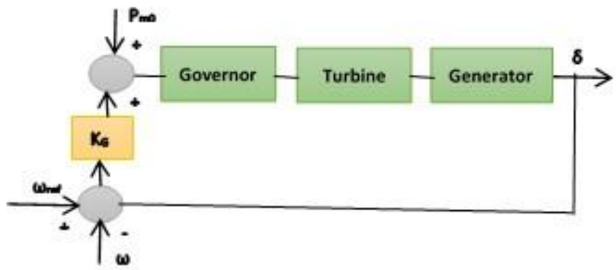


Figure 3. Generator, turbine, and governor model

An integral controller acts on this error to change the load reference of both governors. Since an integral controller drives its input to zero in steady state, it follows that in steady state:

$$B_1\left(\frac{\omega_{ref}-\omega_1}{\omega_0}\right)-\Delta P_{12}=0,\ B_2\left(\frac{\omega_{ref}-\omega_2}{\omega_0}\right)-\Delta P_{21}=0, \text{ and } P_{21}\approx-\Delta P_{12} \tag{12}$$

Losses are assumed to be small, ω_1=ω_2 in steady state and typically ω_{ref}=ω_0

Then it follows that if B_1 and B_2 are greater than zero, ω1=ω2=ω0, and $\Delta P_{21}=0$, which means that in steady state, both frequency deviation and tie line power flow deviation are made to go to zero by the AGC. While any value of the weighting factors which are non-zero gives the same result in steady state, they are chosen such that the transient response is good. We consider the same two generator, two load system, let Generator 1 and load at bus 1 be in Area 1 and Generator 2 and load at bus 2 be in area 2. The line between bus 1 and 2 is the inter-area tie line suppose that the aim of the AGC is to keep interchange between the two areas via the tie line zero as well as bring the deviation in frequency to zero.

The action of AGC and governor is represented as follows: Generator power is given by: P_{mi}=P_{m0i}+ΔP_{mi}, governor action on both generators causes a change in power ΔP_{mi} as follows:

$$\Delta P_{mi}=\left(C_{Gi}\left(\frac{\omega_{ref}-\omega_i}{\omega_0}\right)+\Delta P_{m0i}\right)\left(\frac{0.2s+1}{0.7s+1}\right) \tag{13}$$

Where, ΔP_{m0i} represents the change in the load reference due to AGC, which is given by the following transfer function:

$$\Delta P_{m01}=\frac{k_1}{s}\left(B_1\left(\frac{\omega_{ref}-\omega_1}{\omega_0}\right)-\Delta P_{12}\right) \tag{14}$$

$$\Delta P_{m02}=\frac{k_2}{s}\left(B_2\left(\frac{\omega_{ref}-\omega_2}{\omega_0}\right)-\Delta P_{21}\right)\approx\frac{k_2}{s}\left(B_2\left(\frac{\omega_{ref}-\omega_2}{\omega_0}\right)+\Delta P_{12}\right) \tag{15}$$

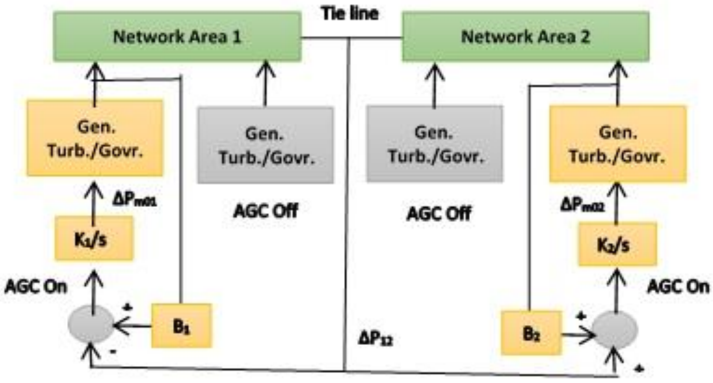


Figure 4. Measured deviation in power flow on tie line ΔP12 with AGC

The values k_1, k_2, B_1, and B_2 are decided based on obtaining good time response no overshoots and undershoots. Note that $\Delta P_{21} \approx -\Delta P_{12}$, losses are assumed to be small. We now see what happens for a 10% load change at bus 1 by numerical integration of the differential equations. Assume that: B_1=B_2=20, and k_1=k_2=0.01

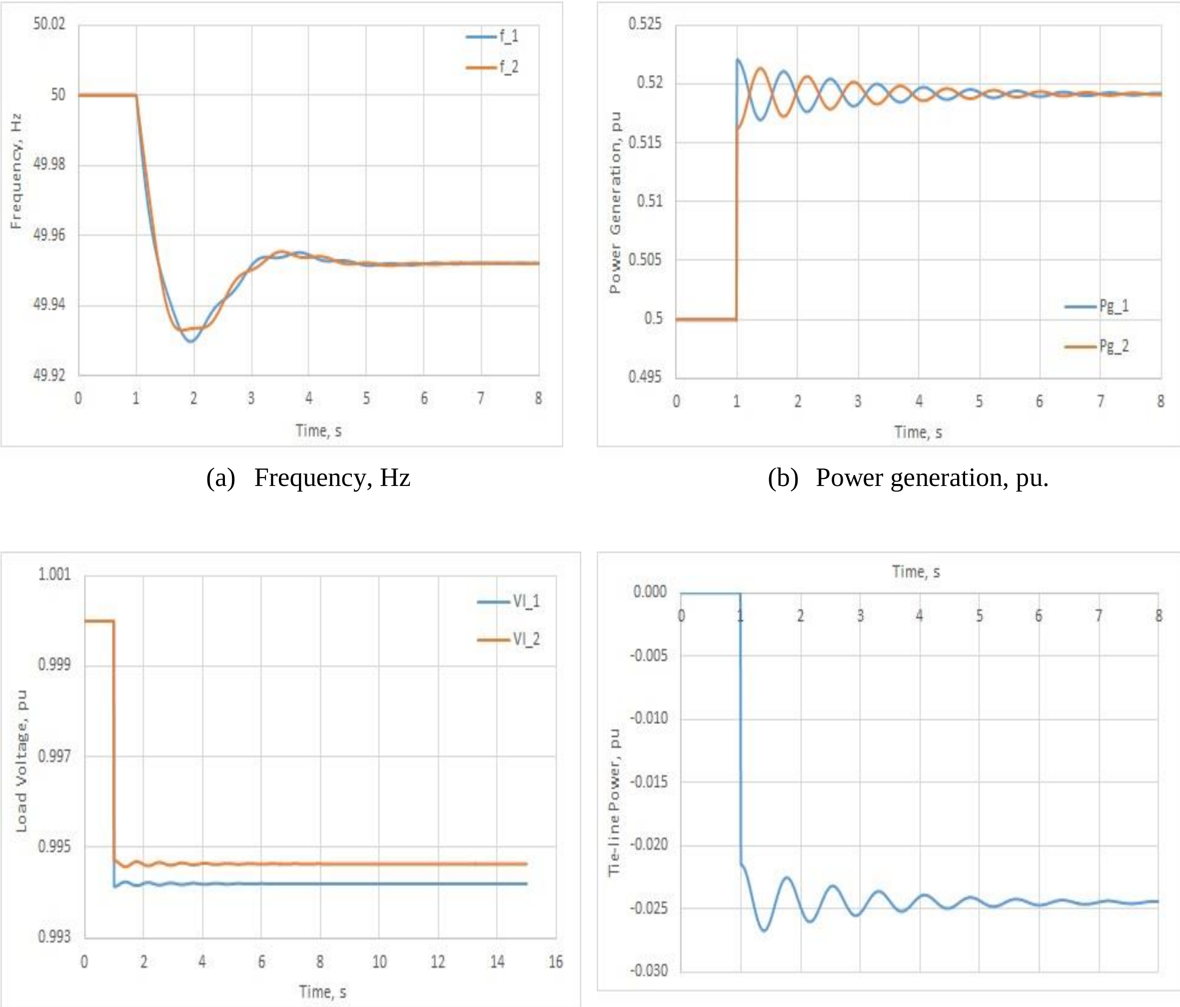
$$B_1\left(\frac{\omega_{ref}-\omega_1}{\omega_0}\right) - \Delta P_{12} = 0 \tag{16}$$

$$B_2\left(\frac{\omega_{ref}-\omega_2}{\omega_0}\right) - \Delta P_{21} = 0 \tag{17}$$

And $\Delta P_{21} \approx \Delta P_{12}$ losses are assumed to be small, ω_1=ω_2 in steady state and typically ω_{ref}=ω_0. Therefore: It follows that if B_1 and B_2 are nonzero, ω_1=ω_2= ω_0, and ΔP_{12}=0. Please read the notes given on the figure to understand the behavior of the AGC.

5. RESULTS AND DISCUSSIONS

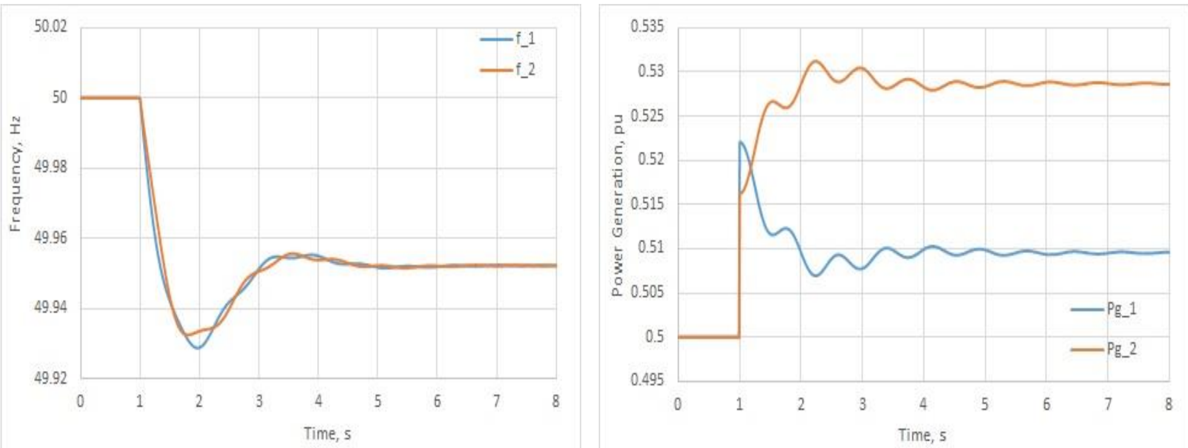
The results of the numerical integration using a MATLAB/SIMULINK simulation model as shown in Figure 2. For the step increase in load #1 by 10%, and the effect of a droop C_{G1}=20 and C_{G2}=20 shown in Figure 5. Also, we discussed the changes in generator speeds, the aggregate movement as well as the relative motion, power output of both machines, voltages at both load buses, and power flow through the tie line between buses #1 and #2 for C_{G1}=30 and C_{G2}=10 as shown in Figure 6. The generator with a larger C_G takes on more load. The values of C_{Gi} not only determine the sharing, but also the speed of response. Since $C_{Gi}(1/s)$ is infinite in steady state, ω_{refi}-ω_i has to be equal to zero for ΔP_{mi} to be finite. In order words, the droop of this speed governor characteristic is zero as shown Figure 7. We have discussed in detail the consequences of having one or more than one generator having droop zero. If generator 1 has the integral speed governor, then it takes on all the load change as shown in the Figures 5, and 6. However we emphasize the point that it is not feasible to have integral type speed governors (or equivalently zero droop characteristics) on more than one generator in the system; non-zero droops on all machines is preferable for load sharing among generators. Frequency of both generators with 10% increase in Load 1 that after initial drop in speed AGC forces that frequency to come to 50Hz slowly. Power output of both generators with 10% increase in Load 1 increase after load change of both generator powers due to governor action. For both generators initially respond and increase these power due to governor action. However due to AGC generator 1 slowly takes on the complete burden of the load increase. Change of power flow 1-2 with 10% increase in Load 1 that initially some benefit of the load increase is shared by generator 2 which increases its power thus power from generator 2 reaches load 1 via that tie line the AGC slowly corrects this deviation and brings back power flow to its old value zero as shown Figure 8



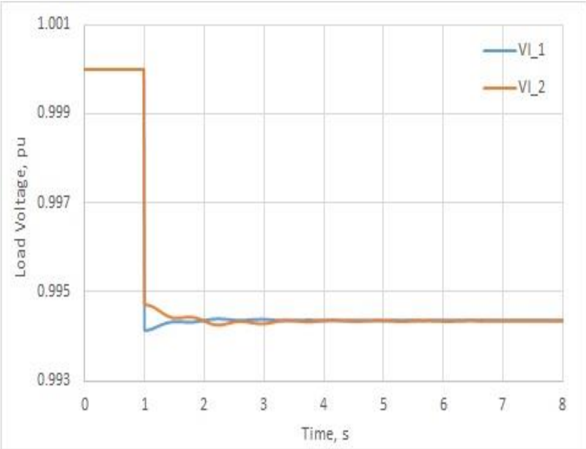
(a) Frequency, Hz (b) Power generation, pu.

(a) Load voltages, pu (d) Tie-line Power flow, pu

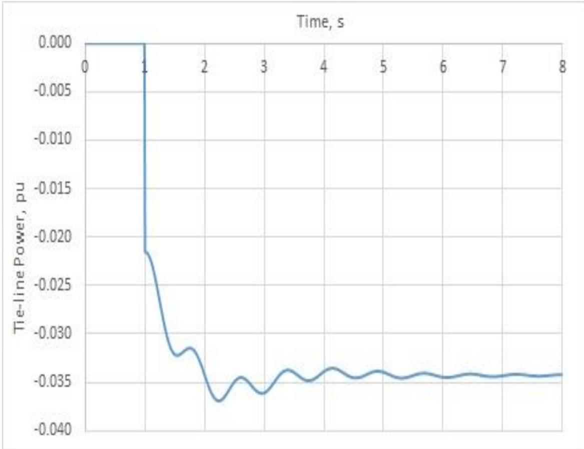
Figure 5. The variation parameters with load #1 is increased by 10%, and C_{G1}=20 and C_{G2}=20



(a) Frequency, Hz (b) Power generation, pu.

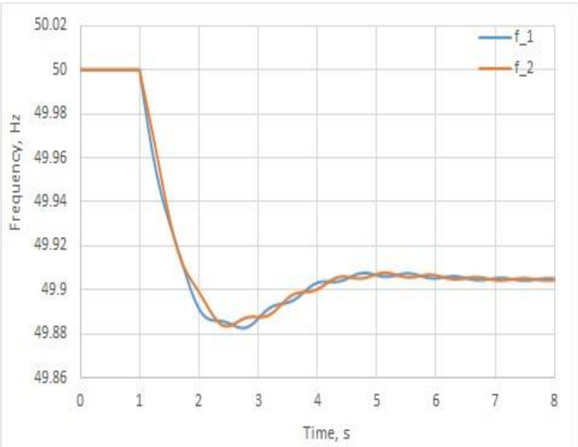


(c) Load voltages, pu

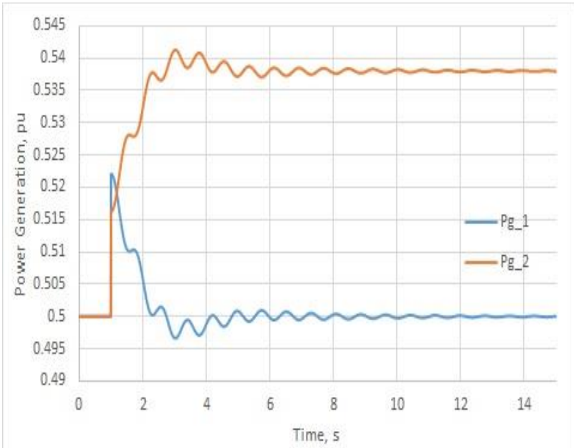


(d) Tie-line Power flow, pu

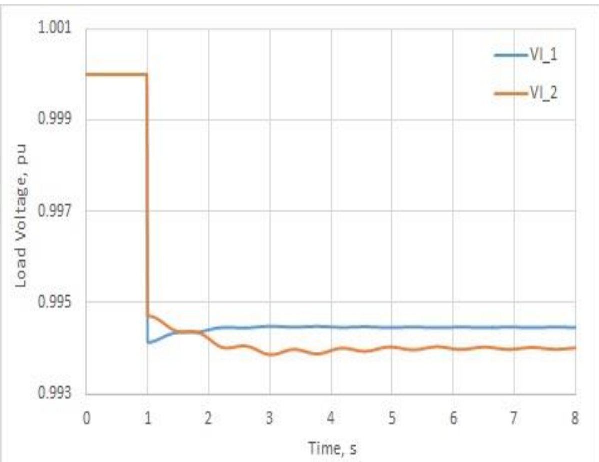
Figure 6. The variation parameters with load #1 is increased by 10%, and C_{G1}=30 and C_{G2}=10



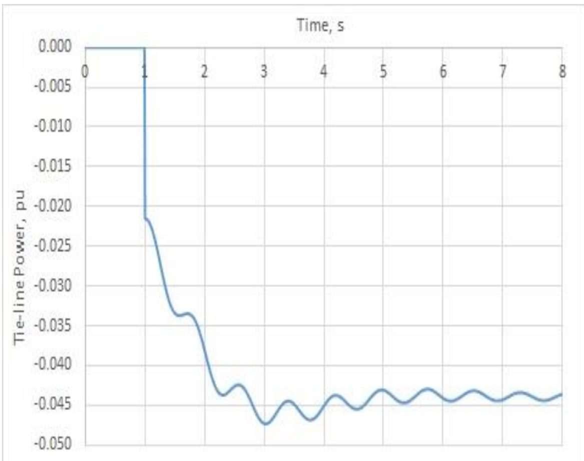
(a) Frequency, Hz



(b) Power generation, pu.

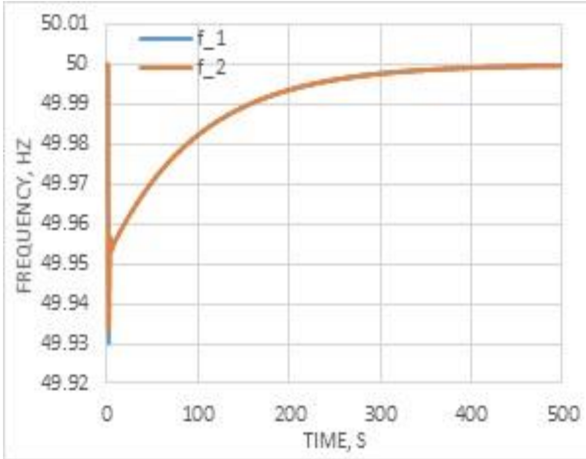


(c) Load voltages, pu

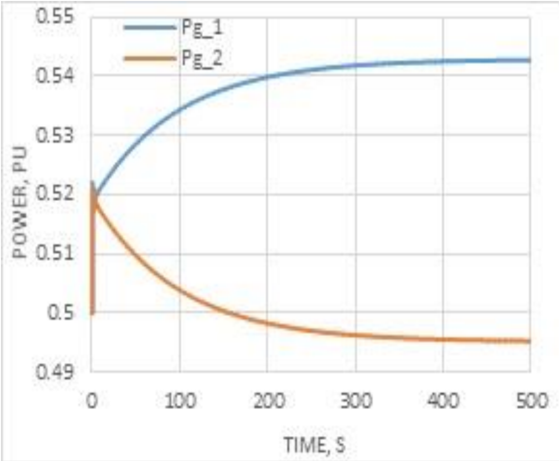


(d) Tie-line Power flow, pu

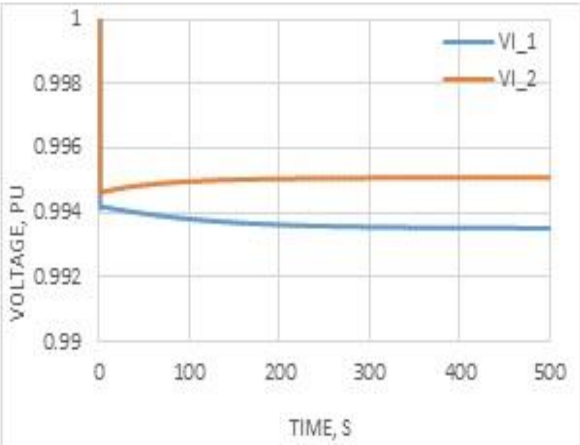
Figure 7. The variation parameters with load #1 is increased by 10%, and C_{G1}=30 and C_{G2}=0



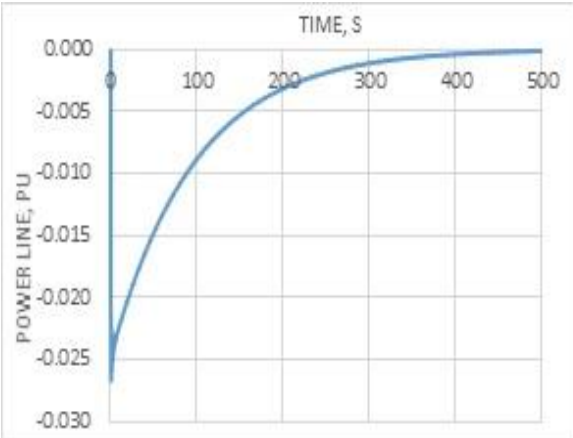
(a) Frequency, Hz



(b) Power generation, pu.



(c) Load voltages, pu



(d) Tie-line Power flow, pu

Figure 8. The variation parameters with load #1 is increased by 10%, with the AGC

6. CONCLUSION

Load generation imbalance causes decline or rise in the speeds of synchronous machines connected in the system. If prime movers deliver a constant power, the equilibrium value of frequency is determined by the frequency dependence of loads. Since this dependence is weak, the frequency decline or rise due to load-generation imbalance can be quite high prime mover control is done by making prime mover power a function of the speed. Then speed governors prevent sudden large rise or fall in speed. The steady state scheduling of generators based on economic factors is done by changing the load reference of the prime mover manually. Therefore there is a hierarchy of prime mover controls, operating on three different time scales which decide the final generator output. In emergency situations wherein large load-generation imbalance exists generator or load tripping may be required to prevent large frequency changes.

The sharing of extra load by generators is determined by the droop of speed governors. The droop is related to the steady state proportional gain given to the speed error. Due to proportional gain feature, a steady state error in frequency will remain when a governor causes a steady state change in prime mover power. Therefore frequency regulation by a governor is not perfect, but permits a droop so that sharing can be achieved conveniently. Frequency can be brought back to the nominal value and inter-area power flow can be regulated by another slow acting control loop which controls prime mover output in a few generators in each area by using AGC. It is important to note that an AGC is much slower acting than a speed governor

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