RESTORATION OF FREQUENCY DUE TO VARIATION OF LOAD IN AN AUTONOMOUS MICROGRID

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APPROVAL

The Project entitled "RESTORATION OF FREQUENCY DUE TO VARIATION OF LOAD IN AN AUTONOMOUS MICROGRID" submitted by Md. Alamgir, ID no 10271006 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Engineering in Electrical and Electronic Engineering on 24 April 2018.

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Chapter 1

Introduction

1.1 Introduction

A Microgrid [1] is a mediumor low voltage distribution networks which comprises various distributed generations (DGs), controllable loads and storage devices. The generations are actually a mix of conventional, solar, wind, fuel cell, etc. Microgrid may be operated in interconnected or isolated mode from the main distribution grid as a controllable subsystem [2]. Microgrid provides a new pattern for defining the operation of DGs from the point of view of both the utility and the customer. The microgrid can be considered as a controllable group of the power system. For example, microgrid can be control as a single dispatch able load, which can respond in seconds to meet the requirements of the transmission system. The microgrid can also be designed to fulfill the customers' special requirements such as for local reliability development, feeder loss decrease, local voltage support, voltage sag adjustment, and increase of the efficiency through use of waste heat and so on[3].

In grid-connected mode, the microgrid will be electrically connected to the main network both being supplied by the network or injecting power to the network [4].If there is a fault in the main grid, the microgrid should have the ability to be operate in an islanded mode.

The important control tasks of a microgrid are the regulation of the system frequency and voltage magnitude, in the islanded mode. The power versus frequency droop control is the universally used process to ensure power sharing and the frequency/ voltage synchronization [5], because it is easy to implement and it enables decentralized control of various distributed generations (DGs). But, by using existing droop controller, the frequency of an autonomous microgrid will endlessly change according to the variation of load requirement [6]. Also, since the droop control method is basically a steady-state measure, the dynamic characteristics of differentenergy sources are not taken into consideration.

The largest part of these distributed energy generators consist ofvariable-frequency ac sources, high-frequency ac sources or dc sources, and for this reason, they need dc–ac converters, also called inverters, to interface with the public-utility grid [7]. For instance, wind turbines [8] are most efficient if free to generate at variable frequency, and so, they require conversion from variable frequency ac to dc to ac; miniature gas-turbines with direct drive generators [9] control at high frequency and also need ac to dc to ac conversion; photovoltaic arrays [10] require dc–ac conversion. This means that almost in all cases inverters will be connected to the grid and will dominate power generation. So the dynamic characteristic of inverter cannot be neglected.

Because of completely different characteristics of conventional generators with renewable sources of generation, it is very difficult to propose a single method which will be applicable for both types of generation. Therefore, first of all a concept of unifying the renewable energy sources with the conventional sources has been presented. This is to operate the inverters used in the renewable sources exactly similar to a synchronous generator, naming it as 'Synchroconverter' [11].

Once the conventional and non-conventional generators are combined a common method for controlling the frequency of a system, for a change of load can be determined. This project describes a method of controlling the system frequency of a microgrid at different operating conditions.

1.2 Literature Survey

The application of microgrid is increasing day by day according to the requirement of humanity, in present time a verity of research have been carried out about the basic designof microgrid and Secondary load frequency control. Bo Zhaoet.al [12] proposed an integrated microgrid system with flexible formation and dependable distributed generations and energy storage systems.According to their paper the small microgrids can operate separately or in grid-connected mode by using master-slave control strategy. Shervin Mizani, et.al [13] elaborates that optimal selection of renewable distributed generations are in conjunction with an optimal dispatch strategy, can significantly reduce the microgrid lifetime cost and emission. Theypresent an optimal microgrid configuration withmathematical model and optimization algorithm.

But the secondary load frequency control is an important issue for microgrid, Paolo Piagi [14] et.al elaborated that secondary load frequency can be control by controlling the power vs frequency droop control.Because when the microgrid is connected to the grid, loads receive power both from the grid and from local microsources, depending on the customer's situation, this situation requiresthe power vs frequency droop control. Hemanshu R.Pota [15] explain the use of droop control system to distribute load changes between inverter-sourced generators in an autonomousmicrogrid. When the load changes within the microgrid, the inverter-sourced generators will share this change in loadand for this he proposes a controller and sensor dynamics model to interact for a stable operation. Mojtaba Khederzadeh [16] describes aformulato stabilize the frequency in normal and emergency condition based on the new bilateral communication infrastructure within aMicrogrid, and for this demand reserves technic are used based on a pre-scheduledsetting instead of shedding loads or applying generation resources. A.Madureira, et.al [17] demonstrate that a microgrid Central Controller (MGCC) can be added to the microgridthat system able to assure stable and secure operation when themicrogrid is on islanding mode.

Qobad Shafiee et.al [18] placed a concept to imagine the secondary approach.A distributed networked control system is used in order to implement a distributed secondary control (DSC) instead of MGCC. The proposed idea is not only able to restore frequency and voltage of the microgrid to the nominal value but also ensures reactive power sharing. The distributed secondary control does not defends on a central control, so that the failure of a single unit will not produce the fail down of the whole system. Here every DG has its own local secondary control which canproduce appropriate control signal for the primary control levelby using the measurements of other DGs in each sample time by acommunication latency, this latency is considered whensending/receiving information to/from other DG units and theresults are compared with the conventional MGCC. Seon-Ju Ahn et.al [19] elaborated that the secondary load frequency control of a microgrid is important issue thus they proposes a new frequency control technique foran islandedmicrogrid with various DGs to ensure the constant system frequency. As their proposal an integral controller is addedto the existing droop controller for this function. As their investigation they use simple two DGs model. Firstly, the effects of various control parameters, such as integral gain and droop constant. According to these investigations, a method to determine the control parameters considering the dynamiccharacteristics of various DGs is proposed.Torestore the system frequency to the nominal value within limited time and also ensure the propersharing between multiple DGs wasthe objectives of the proposed method.

Constanza Ahumada et.al [20] has claimed about using conventional droop control for controlling load frequency ,they said that a disadvantage of this method is that in steady state the frequency of the microgriddeviates from the nominal value, and has to be restored using a Secondary Control System (SCS). The output signal of (SCS) is transmitted using a communication channel to the microgrid to correcting the frequency. But communication channels has some limitation such as prone to time delays which should be considered in the design of the SCS.In their paper, they proposed two new SCSs control schemes are explained to deal with this issue:1. Model Predictive Controller (MPC) and 2.Smith predictor based controller. The performance of both control methodologies is compared to by using simulation work and they make a decision that MCP has better performance. Emanuel Serban et.al [21] describes a pseudo-droop control structure integrated within a microgrid systemthrough Distributed Power Generation (DPG) modules capable to function in off-grid islanded, genset-connected and grid-connected modes of operation. Theyproposed a control strategy in off grid islanded mode method based on the microgridline frequency control as agent of communication for energy control between the DPG modules. When the AC load demand decreasethan the available power from the photovoltaic solararray where the battery bank may be overcharged with unrecoverable damage consequences. The DPGmodule controls the battery charge with a frequency generator function and the DPG current source module controls its output current through a frequency detection function.

Jun Yang, at.al [22] Present a LFC model of an isolated micro-grid with EVs, distributed generations and their constraints is developed. In addition, a controller based on multivariable generalized predictive control (MGPC) theory is proposed for LFC in the isolated micro-grid, where EVs and diesel generator (DG) are coordinated to achieve a satisfied performance on load frequency. A standard isolated micro-grid with EVs, DG, and wind farm is modeled in the MATLAB/Simulink environment to demonstrate the effectiveness of the proposed method. Simulation results establish that with MGPC, the energy stored in EVs can be managed intelligently according to LFC requirement. This improves the system frequency stability with complex operation situations including the random renewable energy resource and the continuous load disturbances.

1.3 Objective of the project work

Three objectives were set for the project work. They are:

(a) To develop a system for unifying the alternative energy sources with conventional generations.

(b) To propose a load-frequency control strategy for the restoration of frequency with the variation of load.

(c) To develop a rule for generalized control of generations of varying characteristics.

1.4 Organization of this report

This project paper is organized in five chapters. Chapter 1 describes an introduction of the topics in general. It also includes a description of literature survey containing an analysis of previous related work and highlights of their limitations. The scope of the present work is also described in this chapter

Chapter 2 describes the concepts of synchronverter.Its formulation and application in microgrid have been elaborated in this chapter.

Chapter 3 elaborates the representation of microgrid. The main topic of this chapter is the description of the representation of different distributed generators comprising a microgrid. On the basis of the representation of the components of a microgrid the control aspects are presented in this chapter.

Chapter 4 contains the results of the present work. A simulation of load-frequency control has been presented in this chapter. Starting with a description of the system studied, the cases of simulation has been explained in this chapter. The outputs of the simulation are presented in graphical form. Finally a rule-based control algorithm has been developed for application of this work in generalized microgrid.

The project paper is concluded in chapter 5. Apart from the conclusion of the work the scope future work has been presented in this chapter.

Chapter 2

Synchronverter

2.1 What is Synchronverter?

For economic, technical, and environmental reasons, the share of electrical energy produced by distributedenergy sources, such as combined heat and power (CHP) plants, and renewable-energy sources,such as wind power,solar power, wave and tidal power, etc., is steadily increasing.Most of these distributed/renewable-energy generators comprisevariable-frequency ac sources, high-frequency ac sources, or dc sources, and hence, they need dc–ac converters, also called inverters, to interface with the public-utility grid. For example wind turbines need conversion from variable frequency ac to dc to ac, small gas turbine will require conversion from ac to dc to ac, photovoltaic arrays require dc to ac conversion. This means that more and more inverters will be connected to the grid and will eventually dominate power generation.

Now the key problem here is how to control the inverters in distributed power generators. There are two options, the first is to redesign the whole power system and to change the way it is operated and the second is to find a way so that these inverters can be integrated into the existing system and behave in the same way as large synchronous generator (SG) can do. I think that the second option has the advantages, as it would assure a smooth transition to a grid dominated by inverters. The inverters that are operated in this way is called a synchronverters [11]. Using synchronverters, the well-established theory used to control SGs can still be used in power systems where a significant proportion of the generating capacity is inverter-based.

The dynamic equations are the same; only the mechanical power exchanged with the prime mover in conventional SGs is replaced with the power exchanged with the dc bus in an inverter. I call such an inverter (including the filter inductors and capacitors) and the associated controller a synchronverter.To be more precise, a synchronverter is equivalent to an SG with a small capacitor bank connected in parallel to the stator terminals. A sychronverter will have all the good and bad properties of an SG, which is a complex nonlinear system. For example, the undesirable phenomena, such as loss of stability due to underexcitation as well as hunting could occur in a synchronverter. An advantage is that we can choose the parameters, such as inertia, friction coefficient, field inductance, and mutual inductances suitable for best operation of the inverter. We can choose parameter values that are impossible in a real SG, and we can also vary the parameters while the system is operating.

If a synchronverter is connected to the utility grid and is operated as a generator, no difference would be felt from the grid side between this system and an SG. Thus, the conventional control algorithms and equipment that have been developed for SGs driven by prime movers can be applied to synchronverters.

2.2 Implementation of Synchronverter

Now I will describehow to implement a synchronverter. A simple dc/ac converter (inverter) used to convert dc power into three-phase ac (or the other way round) is shown in Fig. 2.1. It includes three inverter legs operated using pulse width modulation (PWM) and LC filters to reduce the voltage ripple (and hence, the current ripple) caused by the switching. In grid-connected operation, the impedance of the grid should be included in the impedance of the inductors L_g(with series resistance R_g), and then we may consider that after the circuit breaker, we have an infinite bus. The power part of the synchronverter is the circuit to the left of the three capacitors, together with the capacitors. If we disregard the ripple, then this part of the circuit will behave like an SG connected in parallel with the same capacitors. The inductors, denoted as L_g, are not part of the synchronverter. It is important to have some energy storage (not shown) on the dc bus (at the left end of the figure) since the power absorbed from the dc bus represents not only the power taken from the imaginary prime mover but also from the inertia of the rotating part of the imaginary SG. What we call the electronic part of the synchronverter is a digital signal processor (DSP) and its associated circuits, running under a special program, which controls the switches. These two parts interact via the signals e and i (v and vg will be used for controlling the synchronverter). The various voltage and current sensors and the signal conditioning circuits and analog/digital converters should be regarded as part of the electronic part of the synchronverter. Normally, the program on the DSP will contain also parts that represent the controller of the synchronverter

The synchronverter are two part, power part and electronic part.

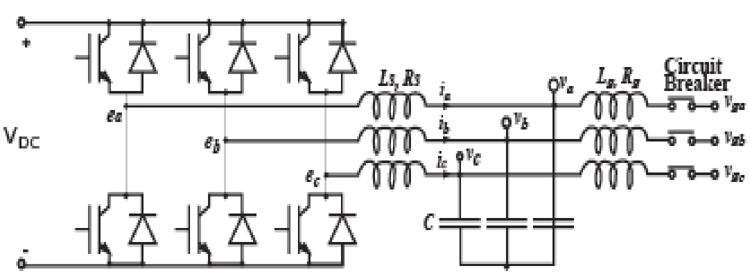

Fig. 2.1. Power part of a synchronverter—a three phase inverter, including LC filters.[11]

A. Power part

If we want to design the power part of the synchronverter, it is important to understand that the terminal voltages$v = [v_a\ v_b\ v_c]^T$of the imaginary SG, are represented by the capacitor voltages shown in Fig.2.1. Further, the impedance of the stator windings of the imaginary SG is represented by the inductance Ls and the resistance Rs of the left inductors shown in fig.2.1. It follows from here that e_a, e_b, and e_c should represent the back EMF due to the movement of the imaginary rotor. This is not possible exactly because e_a, e_b, and e_c are high frequency switching signal, but it is possible in the average sense. The switches in the inverter should be operated so that the average values of ea, eb, and ec over a switching period should be equal to e. This can be achieve by the usual PWM technique.

It is advantageous to assume that the imaginary field winding of the synchronverter is fed by an adjustable dc current sources if instead of a voltage source v_f. Then, the terminal voltage v_f varies, but this is irrelevantaslong as if is constant, the generated voltage,$e = \dot{\theta} M f i \, sin\tilde{\theta}$

B. Electronic part

$J\ddot{\theta} = T_m - T_e - D_p\dot{\theta}$where J is the moment of inertia of all the parts rotating with the rotor, Tm is the mechanical torque, Te is the electromagnetic toque, and D_p is a damping factor. Te can be found from the energy E stored in the machine magnetic field. Now $\ddot{\theta} = \frac{1}{J}(T_m - T_e - D_p\dot{\theta})$where the mechanical torque T_m is a control input, while the electromagnetic torque T_e depends on i and θ,this is the electronic part of asynchronverter shown in Fig. 2.2. Thus, the state variables of the synchronverter are i (the inductor currents), v (the capacitor voltages), θ, and $\theta^{\cdot}$ (which are a virtual angle and a virtual angular speed). (In the absence of a neutral line, only two of the three currents in the vector i are independent.) The control inputs of the synchronverter are T_m and M_f i_f. In order to operate the synchronverter in a useful way, we need a controller that generates the signals Tm and M_f i_f such that system stability is maintained and the desired values of real and reactive power are followed.

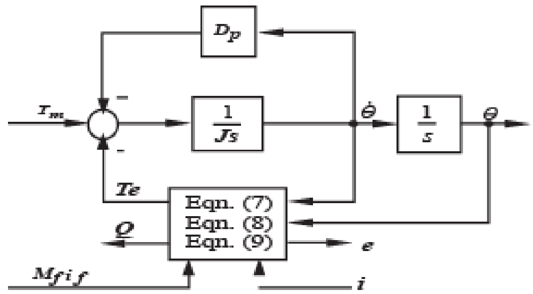

Fig. 2.2. Electronic part of a synchronverter (without control). This part interacts with the power part via e and I, [11]

2.3 Operation of Synchronoconverter

Frequency Drooping and Real Power Regulation : We know that in a SGs, [1] the rotor speed is maintained by the prime mover, and it is known that the damping factor D_p is due to mechanicalfriction. An important mechanism for SGs to share load evenly(in proportion to their nominal load) is to vary the real powerdelivered to the grid according to the grid frequency, which isa control loop called "frequency droop." When the real-powerdemand increases, the speed of the SGs drops due to increased T_e. The power regulation system of the prime mover thenincreases the mechanical power, e.g., by widening the throttlevalve of an engine, so that a new power balance is achieved.Typical values for the frequency droop are a 100% increasein power for a frequency decrease between 3% and 5% (fromnominal values).

The frequency-droop mechanism can be implemented in asynchronverter by comparing the virtual angular speed $\dot{\theta}$ withthe angular frequency reference $\dot{\theta}r$ (which normally would beequal to the nominal angular frequency of the grid $\dot{\theta}n$) and adding this difference, multiplied with a gain, to the activetorque Tm. The formulas show that the effect of the frequencydroopcontrol loop is equivalent to a significant increase ofthe mechanical friction coefficient D_p. The constant

D_p represents the (imaginary) mechanical-frictioncoefficient plus the frequency-drooping coefficient (the latteris far larger). Thus, denoting the change in the total torqueacting on the imaginary rotor by ΔT and the change in angular frequency by $\Delta\dot{\theta}$, we have $D_p = -\frac{\Delta T}{\Delta\dot{\theta}}$Dpis defined as $-\Delta\dot{\theta}/\Delta T$. Here, the negative sign is to make D_p positive. The active torque Tm can be obtained from the setpoint(or reference value) of the real power P_{set} by dividing it withthe nominal mechanical speed $\dot{\theta}_n$, Because of the built-in frequency-drooping mechanism, a synchronverterautomatically shares the load variations with other inverters ofthe same type and with SGs on the same power grid. The realpower regulation loop is very simple because no mechanical devices are involved, and no measurements other than i are needed (all the variables are available in the DSP).

Chapter 3

Load frequency control of a microgrid

3.1 Components of a microgrid

A Micro grid is a semiautonomous grouping of generating sources and end-use sinks that are placed and operated for the benefit of its members, which may be one utility customer, or a grouping of several sites. The supply sources may include reciprocating engine generator sets,wind turbines,micro turbines, fuel cells, photovoltaic arrays and other small-scale renewable generators, storage devices, and controllable end-use loads.

Micro grid is a small power system which integrates multiple distributed generators and local loads; it takes advantage of much clean energy like wind and solar, and it is also an effective way to solve the grid connection problem brought by the large number of DG.A microgrid is a small-scale power generation and distribution system that exclusively serves a house or a group of house, providing power at a lower price and providing a shield against power interruptions when the regional grid experiences problems. Solar arrays, combined heat and power (CHP) systems, wind turbines, hydroelectric facilities and other power generators alone or in combination can provide the energy for microgrids.

Figure:3.1 shows the block diagram of an autonomous microgrid, here we have DG_1,DG_2-----DG_N,each DG consist of renewable source and connected in a grid, this grid is also connected to national grid with a isolator.The isolator isolate the microgrid when a fault occurs in national grid.

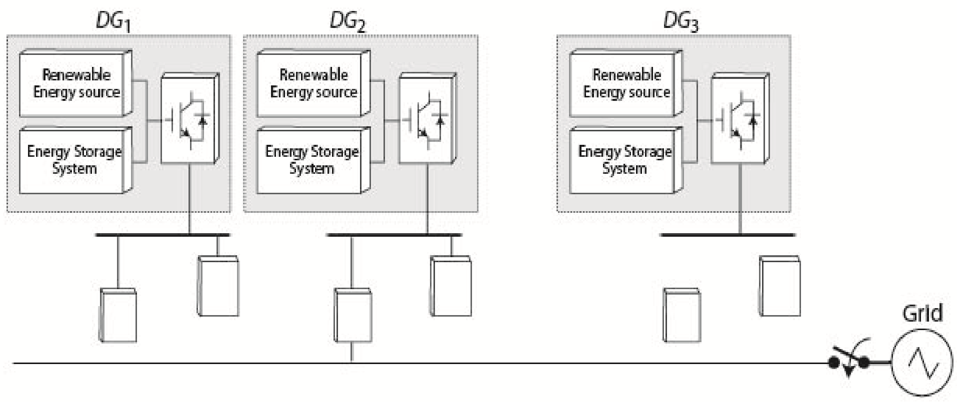

Fig: 3.1. Autonomous Microgrid. [18]

3.2 Controlling a generator

3.2.1 Balance between Mechanical and Electrical Torque

Agenerator driven by a steam turbine can be represented as a large rotating mass with two opposing torques acting on the rotation [24]. As shown in Figure 3.2, T_{mech} the mechanical torque, acts to increase rotational speed whereas T_{elec}, electrical torque, acts to slow it down. When T_{mech} & T_{elec},, are equal in magnitude, the rotational speed, ω, will be constant. If the electrical load is increased so that T_{elec} is larger than T_{mech} the entire rotating system will begin to slow down.

Since it would be damaging to let the equipment slow down too far, something must be done to increase the mechanical torque T_{mech} to restore equilibrium; that is, to bring the rotational speed back to an acceptable value and the torques to equality so that the speed is again held constant.

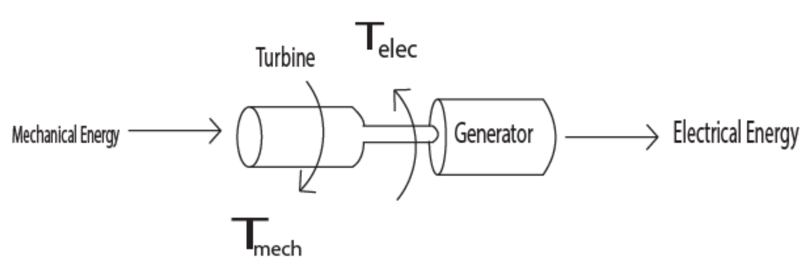

Fig: 3.2: Mechanical and electrical torques in a generating unit. [24]

Because there are many generators supplying power into the transmission system, some means must be provided to allocate the load changes to the generators. To accomplish this, a series of control systems are connected to the generator units. A governor on each unit maintains its speed with supplementary control. In the development to follow, we are interested in deviations of quantities about steady-state values. All steady-state or nominal values will have a "0" subscript (e,g.,ω_0,T_{net0}) and all deviations from the nominal will be designed by a "Δ"(e,g., Δω, ΔT_{net}). To start, we will focus our attention on a single rotating machine. Assume that the machine has a steady speed of $\omega_0$and phase angle δ_0,. Due to various electrical or mechanical disturbances, the machine will be subjected to differences in mechanical and electrical torque, causing it to accelerate or decelerate. We are chiefly interested in the deviations of speed, Δω, and deviations in phase angle, Δδ, from nominal. The relation between Δω and the difference between ΔP_{mech} and ΔP_{elec} is shown in Fig: 3.3

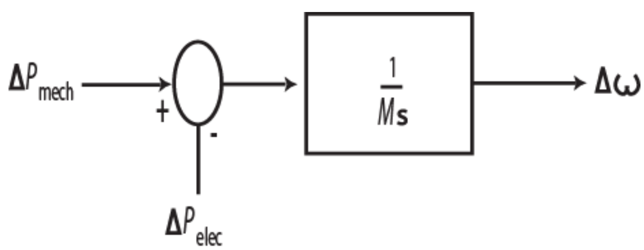

Fig: 3.3: Relationship between mechanical and electrical power and speed change.[24]

3.3 Load representation

The loads on a power system consist of a variety of electrical devices. Some of them are purely resistive, some are motor loads with variable power frequency characteristics, and others exhibit quite different characteristics. Since motor loads are a dominant part of the electrical load, there is a need to model the effect of a change in frequency on the net load drawn by the system. The relationship between the changesin load due to the change in frequency is given by

$$\Delta P_{L(freq)} = D\Delta_{\omega} \quad \text{Or}$$

$$D = \frac{\Delta P_{L(freq)}}{\Delta_{\omega}}$$

Where D is expressed as percent change in load divided by percent change in frequency. For example, if load changed by 1.5% for a 1% change in frequency, then D would equal 1.5.

The representation of load is shown in fig.3.4.

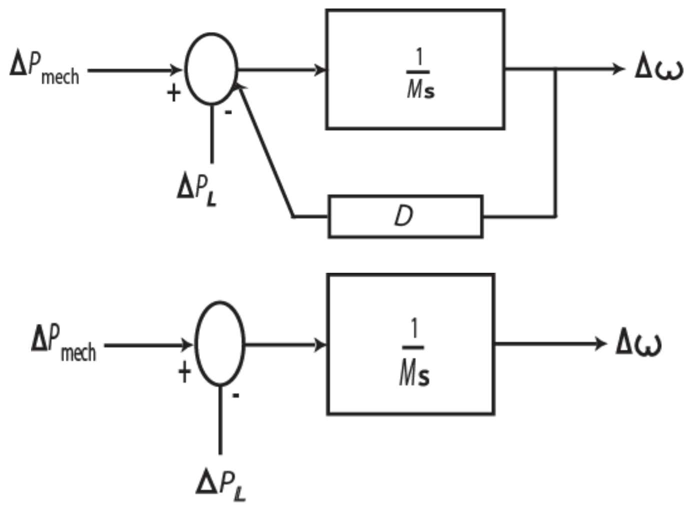

Fig: 3.4: Block diagram of rotating mass and load as seen by prime-mover output.[24]

When two or more generators are connected to a transmission system network, we must take account of the phase angle difference across the network in analyzing frequency changes. However, for the sake of governor analysis, which we are interested in here, we can assume that frequency will be constant over those parts of the network that are tightly interconnected. If we accept such an assumption, we can then lump the rotating mass of the turbine generators together into an equivalent that is driven by the sum of the individual turbine mechanical outputs. This is illustrated in Figure 3.5, where all turbine generators were lumped into a single equivalent rotating mass, M_{equiv}. Similarly, all individual system loads were lumped into an equivalent load with damping coefficient, D_{equiv}.

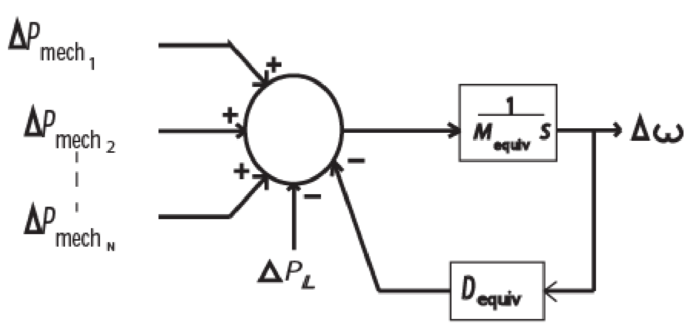

Fig: 3.5. Multi-turbine-generator system equivalent.[24]

3.4 Representation of the prime mover

The prime mover driving a generator unit may be a steam turbine or a hydro turbine. The model for prime mover is depicted in Fig.3.6. The combined prime-mover-generator-load model for a single generating unit can be built by combining Figure 3.4 and 3.6, as shown in Figure 3.7

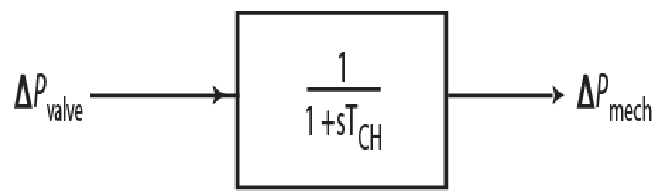

Fig: 3.6. Prime-mover model.[24]

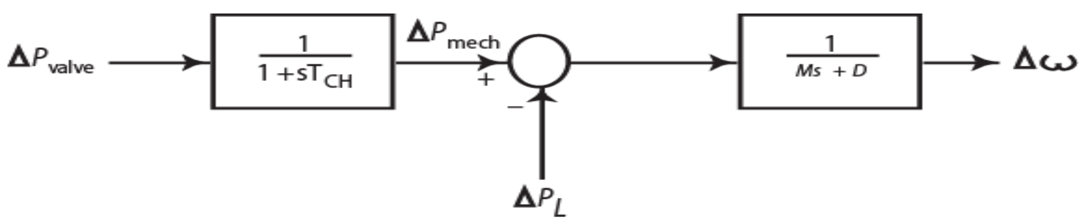

Fig: 3.7: Prime-mover-generator-load model. [24]

3.5 Representation of Governor

If a generating unit is operated with fixed mechanical power output from the turbine. The result of any load change would be a speed change sufficient to cause the frequency-sensitive load to exactly compensate for the load change. This condition would allow system frequency to drift far outside acceptable limits. This is overcome by adding a governing mechanism that senses the machine speed, and adjusts the input valve to change the mechanical power output to compensate for load changes and to restore frequency to nominal value. The earliest such mechanism used rotating "fly balls" to sense speed and to provide mechanical motion in response to speed changes. Modern governors use electronic means to sense speed changes and often use a combination of electronic, mechanical, and hydraulic means to effect the required valve position changes. The simplest governor, called the isochronous governor,(Fig: 3.8) adjusts the input valve to a point that brings frequency back to nominal value. If we simply connect the output of the speed-sensing mechanism to the valve through a direct linkage, it would never bring the frequency to nominal. To force the frequency error to zero, one must provide what control engineers call reset action. Reset action is accomplished by integrating the frequency (or speed) error, which is the difference between actual speeds and desired or reference speed. We will illustrate such a speed-governing mechanism with the diagram shown in Figure 8. The speed-measurement device's output, ω, is compared with a reference ω_{ref}, to produce an error signal, Δω. The error, Δω,

is negated and then amplified by a gain K, and integrated to produce a control signal, ΔP_{valve} which causes the main steam supply valve to open (ΔP_{valve} position) when Δω is negative. If, for example, the machine is running at reference speed and the electrical load increases, ω will fall below ω_{ref} and Δω will be negative. The action of the gain and integrator will be to open the steam valve, causing the turbine to increase its mechanical output, thereby increasing the electrical output of the generator and increasing the speed ω. When ω exactly equals ω_{ref} the steam valve stays at the new position (further opened) to allow the turbine generator to meet the increased electrical load**.**

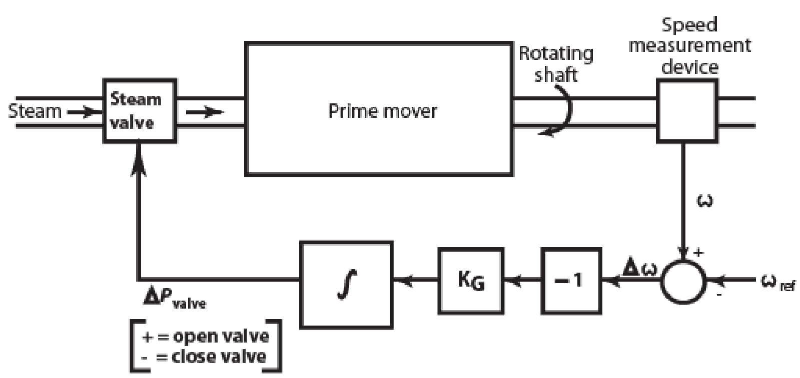

Fig: 3.8: Isochronousgovernor.[24]

3.6 Droop Control

The isochronous (constant speed) governor of Figure 3.8cannot be used if two or more generators are electrically connected to the same system since each generator would have to have precisely the same speed setting or they would "fight" each other, each trying to pull the system's speed (or frequency) to its own setting. To be able to run two or more generating units in parallel on a generating system, the governors are provided with a feedback signal that causes the speed error to go to zero at different values of generator output. This can be accomplished by adding a feedback loop around the integrator as shown in Figure 3.9.

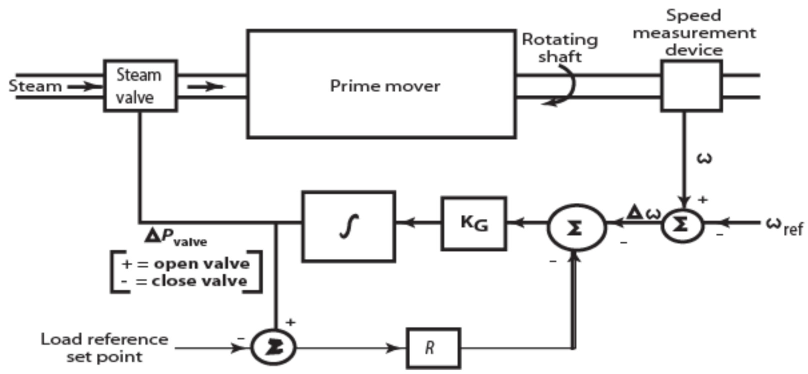

Fig: 3.9. Governor with speed-droop feedback loop.[24]

Note that we have also inserted a new input, called the loud reference that we will discuss shortly. The block diagram for this governor is shown in Figure 3.10, where the governor now has a net gain of 1/R and a time constant TG. The result of adding the feedback loop with gain R is a governor characteristic as shown in Fig.3.11. The value of R determines the slope of the characteristic. That is, R determines the change on the unit's output for a given change in frequency. A typical droop characteristic is shown in fig: 3.11. Common practice is to set R on each generating unit so that a change from 0 to 100% (i.e., rated) output will result in the same frequency change for each unit. As a result, a change in electrical load on a system will be compensated by generator unit output changes proportional to each unit's rated output. If two generators with drooping governor characteristics are connected to a power system, there will always be a unique frequency, at which they will share a load change between them. This is illustrated in Figure 3.12, showing two units with drooping characteristics connected to a common load.

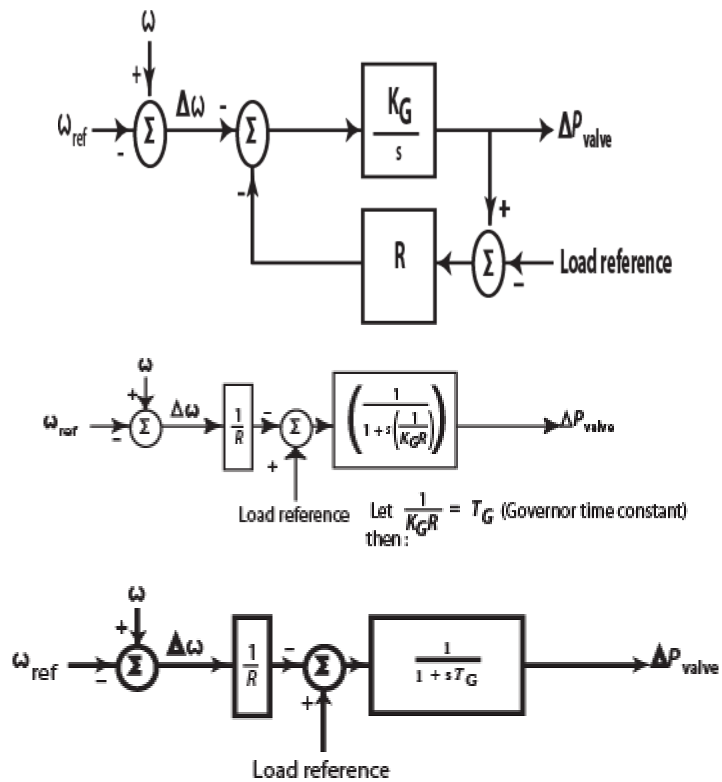

Fig: 3.10. Block diagram of governor with droop.[24]

A typical droop characteristics is shown inFig.3.11

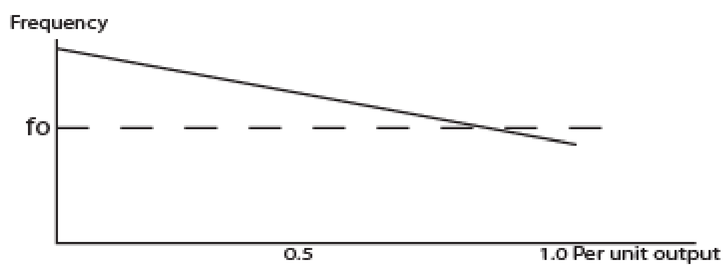

Fig: 3.11. Speed-droop characteristic.[24]

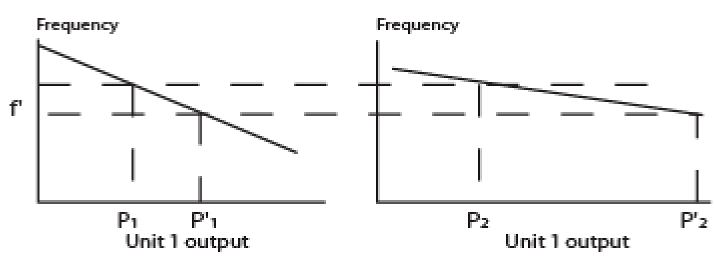

Fig: 3.12. Allocation of unit outputs with governor droop.[24]

As shown in Figure 3.12, the two units start at a nominal frequency of$f0$. When a load increase, ΔPL, causes the units to slow down, the governors increase output until the units seek a new, common operating frequency,f. The amount of load pickup on each unit is proportional to the slope of its droop characteristic. Unit 1 increases its output from P_1 to $\acute{P}_1$, unit 2 increases its output from P_2 to $\acute{P}_2$such that the net generation increase, $\acute{P}_1$- P1+ $\acute{P}_2$- P2, is equal to Δ_{PL}.

Figure 3.9shows an input labeled "load reference set point." By changing the load reference, the generator's governor characteristic can be set to give reference frequency at any desired unit output. By adjusting this set point on each unit, a desired unit dispatch can be maintained while holding system frequency close to the desired nominal value.

3.7 Frequency Restoration

P–f droop based power controllers have proven to be robust and adaptive to variation in the power system operational conditions. However, only with the droop controller, the frequency of an autonomous microgrid will continuously change according to the variation of load demand. In order to restore the frequency to the nominal value, secondary load-frequency control function is necessary. This can be achieved by two different ways. The first approach is to use a central controller, which sets the power reference signal of each DG. The central controller includes a multiplicity of functionalities one of which is secondary load-frequency control. This functionality is similar to the one of a conventional Automatic Generation Control (AGC) system. The central controller coordinates a hierarchical control scheme, where the control infrastructure is shown in Figure 3.13

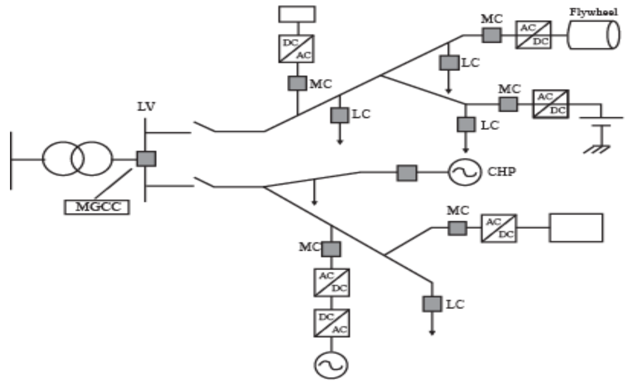

Fig. 3.13. MG central controller, [17]

The central controller is supposed to be installed at the LV side of the MV/LV substation. The central controller interfaces the MG and the distribution network and has several vital functions. At a second hierarchical level each microgenerator and storage device is locally controlled by a Micro source Controller (MC) and each electrical load is locally controlled by a Load Controller (LC). In order to achieve a good performance of the control scheme, an efficient communications infrastructure is necessary.

The other one is to add an integral controller,(Fig: 3.14) to the existing power controller of DGs. Local or conventional primary frequency control is a distributed control system that operates on the imbalance between load and generation through measuring the frequency deviations. Indeed, each generating unit respond to the frequency excursions by its droop characteristic without any communicating signal from the control center. In other words, the generating units that are responsive to frequency changes are self-regulatory units that help to improve the frequency locally without any commanding signal.

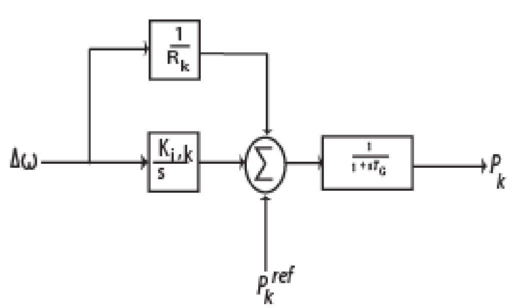

Fig: 3.14.MG Integral controller.[19]

Chapter 4

System Studied

4.1 System Analysis

In order to analyze the effects of the controller parameters on the power sharing of DGs, we use a simple two DG system as shown in Fig. 4.1. In this study, the dynamics of DGs are modeled as a first order system with time constant Tg [25]. System dynamics are also modeled as a first order system, where M is the equivalent inertia constant of generators and D is the damping constant of loads. A simulation platform under the *MatLab® Simulink®*were developed.

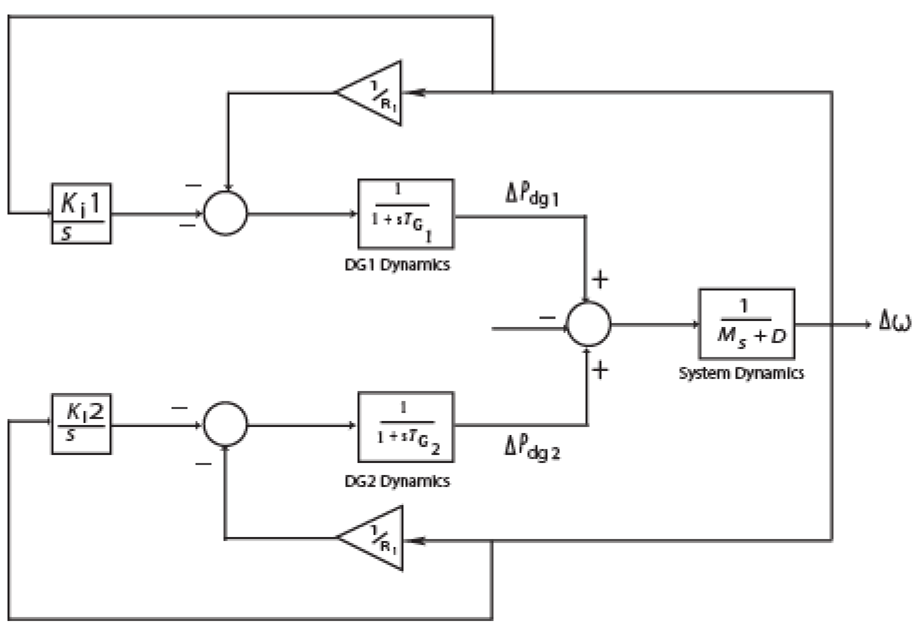

Fig.4.1.Simple two DG system to investigate the effect of controller parameters.[19]

4.2 Result and Analysis

Power output change of DGs and the variation of frequency has been analyzed by assuming that the load increases suddenly. Firstly, two identical DGs case is investigated as a reference as shown in Fig. 4.1. Simulation Fig.is shown in Appendix AFig A.1In this case, 5% droop ($R_1 = R_2 = 0.05$), 10 s time constant for DGs dynamics ($T_{g1} = T_{g2} = 10$), and integral gain of 1 ($K_{i1} = K_{i2} = 1$) are used. Two DGs have the same response and the power is shared evenly. The frequency has an approximately 0.2 pu drop at the initial transient, but it is restored to the nominal value

Table 4.1: Reference Case ($R_1 = R_2 = 0.05$), ($T_{g1} = T_{g2} = 10$), ($K_{i1} = K_{i2} = 1$)

Droop Value	Time constant for DGs dynamics value	Value of integral gain	Frequency Variation
$R_1 = R_2 = 0.05$	$T_{g1} = T_{g2} = 10$	$K_{i1} = K_{i2} = 1$	Reduced up to 0.2pu

4.2.1 Analysis on the Effect of Droop constant

Table 4.2: Analysis on the Effect of Droop constant

Case No	Droop Value	Time constant for DGs dynamics value	Value of integral gain	Frequency Variation
02	$R_1 = R_2 = 0.04$	$T_{g1} = T_{g2} = 10$	$K_{i1} = K_{i2} = 1$	Reduced up to 0.18pu
03	$R_1 = R_2 = 0.03$	$T_{g1} = T_{g2} = 10$	$K_{i1} = K_{i2} = 1$	Reduced up to 0.18pu
04	$R_1 = R_2 = 0.02$	$T_{g1} = T_{g2} = 10$	$K_{i1} = K_{i2} = 1$	Reduced up to 0.12pu
05	$R_1 = R_2 = 0.01$	$T_{g1} = T_{g2} = 10$	$K_{i1} = K_{i2} = 1$	Reduced up to 0.10pu
06	$R_1 = 3R_2 = 0.05$	$T_{g1} = T_{g2} = 10$	$K_{i1} = K_{i2} = 1$	Reduced up to 0.2pu
07	$R_1 = 5R_2 = 0.05$	$T_{g1} = T_{g2} = 10$	$K_{i1} = K_{i2} = 1$	Reduced up to 0.2pu
08	$R_1 = 8R_2 = 0.05$	$T_{g1} = T_{g2} = 10$	$K_{i1} = K_{i2} = 1$	Reduced up to 0.2pu

Effect of Droop constant has been analyzed in several cases, case result shown in Table 4.2. In the second case,the effect of magnitude on droop constant is analyzed, for this case it is considered thattwo DGs have the same droop constant of 4% ($R_1 = R_2 = 0.04$), Simulation Fig.is shown in Appendix A Fig A.2.ThisFig: shows that the results are very similar to the first case, the system reaches steady state faster than the reference case, and the frequency variation is reduced to approximately 0.18pu.

In the third case,it has been considered two DGs have the same droop constant of 3 % ($R_1 = R_2 = 0.03$), Simulation Fig.is shown in Appendix A Fig A.3. This Fig: shows that the results are very similar to the first case, the system reaches steady state faster than the reference case, and the frequency variation is reduced to approximately 0.17pu.

In the 4th case, it has been considered two DGs have the same droop constant of 2% ($R_1 = R_2 = 0.02$), Simulation Fig.is shown in Appendix A Fig A.4. This Fig: shows that the results are very similar to the first case, the system reaches steady state slower than the reference case, and the frequency variation is reduced to approximately 0.12 pu.

In the 5th case, it has been considered two DGs have the same droop constant of 1% ($R_1 = R_2 = 0.01$), Simulation Fig.is shown in Appendix A Fig A.5. This Fig: shows that the results are very similar to the first case, the system reaches steady state very slower than the reference case, and the frequency variation is reduced to approximately 0.10 pu

In the 6th case, it has been considered that droop constant of DG1 is three times greater than that of DG2 while the equivalent droop constant of two DGs are the same as the reference case ($R_1 = 3R_2$, $R_2 = 0.05$). Simulation Fig.is shown in Appendix A Fig A.6. This Fig: shows that steady state values of DG power output and frequency are the same as the first case, and the frequency variation at the initial transient is also the same as the reference case. In other words, the increased load is evenly shared by the two DGs and the frequency is restored to the nominal value and the largest frequency variation is 0.2 pu,andDG2, which has a smaller droop constant, increases more power than DG1 at the initial state.

In the 7th case,it has been considered that droop constant of DG1 is five times greater than that of DG2 while the equivalent droop constant of two DGs are the same as the reference case ($R_1 = 5R_2$, $R_2 = 0.05$), Simulation Fig.is shown in Appendix A Fig A.7. This Fig: shows that the steady state values of DG power output and frequency are the same as the first case, and the frequency variation at the initial transient is also the same as the reference case. In other words, the increased load is evenly shared by the two DGs and the frequency is restored to the nominal value and the largest frequency variation is 0.2 pu, and DG2, which has a smaller droop constant, increases more power than DG1 at the initial state.

In the 8th case, it has been considered that droop constant of DG1 is eight times greater than that of DG2 while the equivalent droop constant of two DGs are the same as the reference case ($R_1 = 8R_2$, $R_2 = 0.05$), Simulation Fig.is shown in Appendix A Fig A.8. This Fig: shows that the steady state values of DG power output and frequency are the same as the first case, and the frequency variation at the initial transient is also the same as the reference case. In other words, the increased load is evenly shared by the two DGs and the frequency is restored to the nominal value and the largest frequency variation is 0.2 pu, and DG2, which has a smaller droop constant, increases more power than DG1 at the initial state

4.2.2 Analysis on the effect of integral gain

Table 4.3: Analysis on the effect of integral gain

Case No	Droop Value	Time constant for DGs dynamics value	Value of integral gain	Frequency Variation
09	$R_1 = R_2 = 0.05$	$T_{g1} = T_{g2} = 10$	$K_{i1} = K_{i2} = 0.5$	Frequency variation in the initial state is very similar to the reference case.
10	$R_1 = R_2 = 0.05$	$T_{g1} = T_{g2} = 10$	$K_{i1} = K_{i2} = 1$	Frequency variation in the initial state is very similar to the reference case.
11	$R_1 = R_2 = 0.05$	$T_{g1} = T_{g2} = 10$	$K_{i1} = K_{i2} = 2$	Frequency variation in the initial state is very similar to the reference case.
12	$R_1 = R_2 = 0.05$	$T_{g1} = T_{g2} = 10$	$K_{i1} = 0.5K_{i2} = 2$	DG1 power variation is 0.2pu and DG2 power variation is 0.8pu
13	$R_1 = R_2 = 0.05$	$T_{g1} = T_{g2} = 10$	$K_{i1} = 0.3K_{i2} = 0.5$	DG1 power variation is 0.4pu and DG2 power variation is 0.6pu
14	$R_1 = R_2 = 0.05$	$T_{g1} = T_{g2} = 10$	$K_{i1} = 0.75K_{i2} = 1.5$	DG1 power variation is 0.3pu and DG2 power variation is 0.7pu

Effect of integral gainhas been analyzed in several cases, case result shown in Table 4.3. In the 9th case, it has been considered that the integral gain of two DG is same ($Ki_1 = Ki_2 = 0.5$). Simulation Fig.is shown in Appendix A Fig A.9.This Fig: shows that the response of DGs and the frequency variation in the initial state is very similar to the reference case.

In the 10th case, it has been considered that the integral gain of two DG is same ($Ki_1 = Ki_2 = 1$). Simulation Fig.is shown in Appendix A Fig A.10.This Fig: shows that the response of DGs and the frequency variation in the initial state is very similar to the reference case.

In the 11th case, it has been considered that the integral gain of two DG is same ($Ki_1 = Ki_2 = 2$). Simulation Fig.is shown in Appendix A Fig A.11.This Fig: shows that the response of DGs and the frequency variation in the initial state is very similar to the reference case.

In the 12th case, it has been considered that the integral gain of two DG is same ($Ki_1 = 0.5$, $Ki_2 = 2$). Simulation Fig.is shown in Appendix A Fig A.12.This Fig: shows that the response of DGs and the frequency variation in the initial state is very similar to the reference case. However, steady state power sharing is different. Also observed that DG1 power variation is 0.2 pu and DG2 power variation is 0.8 pu.

In the 13th case, it has been considered that the integral gain of two DG is same ($Ki_1 =0.3$, $Ki_2 = 0.5$). Simulation Fig.is shown in Appendix A Fig A.13.This Fig: shows that the response of DGs and the frequency variation in the initial state is very similar to the reference case. However, steady state power sharing is different. Also observed that DG1 power variation is 0.4 pu and DG2 power variation is 0.6 pu.

In the 14th case, it has been considered that the integral gain of two DG is same ($Ki_1 = 0.75$, $Ki_2 = 1.5$). Simulation Fig.is shown in Appendix A Fig A.14.This Fig: shows that the response of DGs and the frequency variation in the initial state is very similar to the reference case.

However, steady state power sharing is different. Also observed that DG1 power variation is 0.3 pu and DG2 power variation is 0.7 pu

4.2.3 Analysis on the Effect of T_g

Table 4.4: Analysis on the Effect of T_g

Case No	Droop Value	Time constant for DGs dynamics value	Value of integral gain	Response of DGs
15	$R_1 = R_2 = 0.05$	$T_{g1} = T_{g2} = 10$	$K_{i1} = K_{i2} = 1$	Response of DGs and the frequency variation in the initial state is very similar to the reference case.
16	$R_1 = R_2 = 0.05$	$T_{g1} = 5$ $T_{g2} = 10$	$K_{i1} = K_{i2} = 1$	Initially D_{g1}sare more power than $D_{g2.}$ However, steady state power sharing is same..
17	$R_1 = R_2 = 0.05$	$T_{g1} = 2$ $T_{g2} = 10$	$K_{i1} = K_{i2} = 1$	Initially D_{g1}sare more power than $D_{g2.}$ However, steady state power sharing is same..

Effect of T_g has been analyzed in several cases, case result shown in Table 4.4. In the 15th case, it has been considered that the $T_{g1}$and $T_{g2}$are same time constant ($T_{g1}=T_{g2}=10$). Simulation Fig.is shown in Appendix A Fig A.15.This Fig:shows that, the response of DGs and the frequency variation in the initial state is very similar to the reference case.

In the 16th case, it has been considered that the $T_{g1}$and $T_{g2}$are same time constant ($T_{g1}=5, T_{g2}=10$). Simulation Fig.is shown in Appendix A Fig A.16. This Fig: shows that, the response of two DGs is different from the reference case. Initially D_{g1}sare more power than $D_{g2.}$ However, steady state power sharing is same.

In the 17th case, it has been considered that the $T_{g1}$and $T_{g2}$are same time constant (T_{g1}=2,T_{g2}=10). Simulation Fig.is shown in Appendix A Fig A.17. This Fig: shows that, the response of two DGs is different from the reference case. Initially D_{g1}share more power than D_{g2}. However, steady state power sharing is same.

4.3 Table's summary

From the above investigation, it has been find out the effects of the two controller parameters on the power sharing and frequency variation as follows.

1. With the integral controller, the steady state frequency can be restored to the nominal value whatever thecontroller parameters we select.

2. Droop constant does not affect the steady state powersharing.

3. The maximum frequency deviation at the initial transient depends on the magnitude of the equivalent droop constant of the system.

4. The ratio of droop constant between DGs affects the power sharing at the beginning of the transient.More concretely, the power variation at the initial transient is approximately but not exactly proportionalto the inverse of the droop constant.

5. Steady state power sharing between DGs is determined by the integral gain. Power shared byeach DG in the steady state is exactly proportional to the inverse of the integral gain

4.4 Rule settings

In the previous section, it has been analyzed that the effects of the controller parameters. According to this analysis, I propose the rules to determine the parameters. The objectives are very simple as follows:

1) A DG that can increase or decrease the power output quickly will give more contribution to the power balance at the beginning.

2) Eventually, a DG with higher rating will share more load in the steady state.

3) A DG with small droop constant initially share more load.

For these objectives, the droop constant (R_k) and integral gain ($K_{i,k}$) of DG_k can be determined as follows

$T_{g,k}/R_k$=Constant

S_k/K_k=Constant

Where, $S_k$is the rating of DG_k and T_g,k is the time constant representing the dynamics of DG

Chapter 5

Conclusion

This project work proposed a new power sharing and frequencycontrol method for an autonomous microgrid with variousDGs. The proposed method adopted an additional integralcontroller as well as the existing droop controller and using synchronverter instead of conventional inverter. Using asimple two DG system, the effects of the integral gain anddroop constant on the power sharing and system frequencyare investigated. Based on the analysis, rules to determinethe control parameters considering the dynamic characteristicsof various DGs were proposed. The objectives ofthe proposed method are to restore the frequency to thenominal value within limited time and to ensure the propersharing between multiple DGs considering the rating andthe dynamic characteristics of energy source of DGs. Theeffectiveness of the proposed rules was also demonstratedby simulation results.

There is a lot of future work that can be done to improve the performance of microgrids, further research may be carried out to address the following issues:

Transmission loss in microgrid, How to reduce energy cost in microgrid. Depending on the design of the connection device, a universal connection device would also be easier to model in a microgrid simulation because only the connection device would need to be modeled, not the energy source. Much work can be done to further understand the dynamics of microgrids, and completing the work will realize the full potential of combining distributed generation with microgrid concepts

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Appendix A

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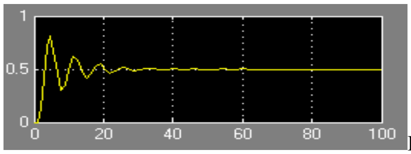
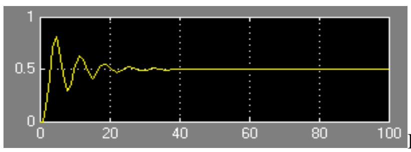
1. **Case 1,**Reference case



Del P dg1

Time(s)



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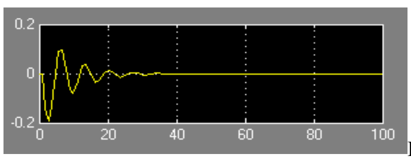
Time(s)

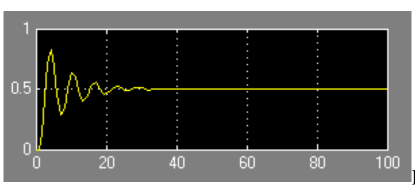


Del f

Time(s)

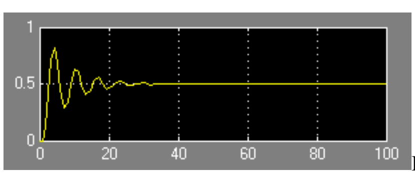
Fig: A.1.Case1: reference case, $R_1 = R_2 = 0.05$, $K_{i1} = K_{i2} = 1$, $T_{g1} = T_{g2} = 10$

2. **Case 2**



Del P dg1

Time(s)



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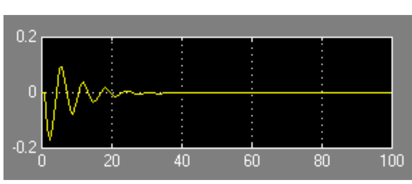
Time(s)

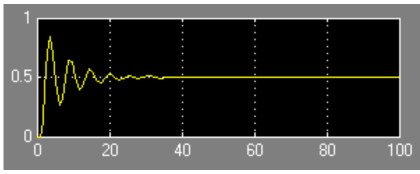


Del f

Time(s)

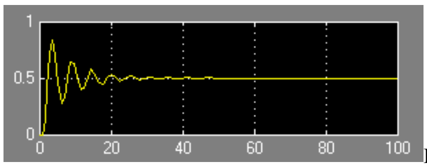
Fig. A.2.Case2: effects of the magnitude of droop constant$R_1 = R_2 = 0.04$, $K_{i1} = K_{i2} = 1$, $T_{g1} = T_{g2} =10$

3. Case 3



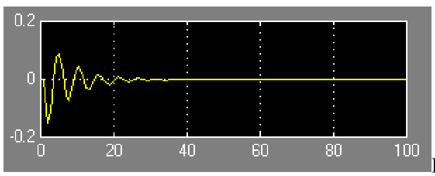
Del P dg1

Time(s)



Del P dg2

Time(s)

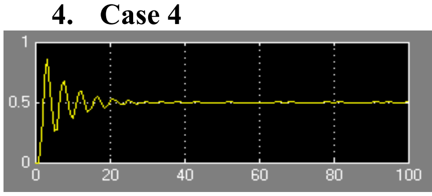


Del f

Time(s)

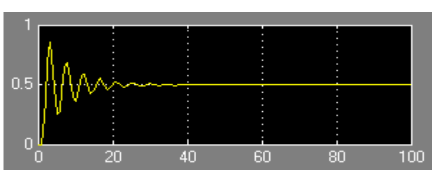
Fig: A.3.Case3: effects of the magnitude of droop constant$R_1 = R_2 = 0.03$, $K_{i1} = K_{i2} = 1$, $T_{g1} = T_{g2}=10$

4. Case 4



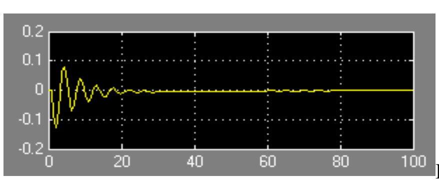
Del P dg1

Time(s)



Del P dg2

Time(s)



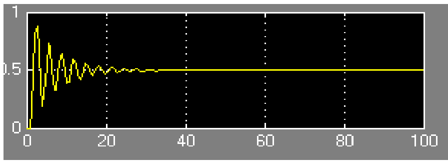
Del f

Time(s)

Fig. A.4.Case4: effects of the magnitude of droop constant$R_1 = R_2 = 0.02$, $K_{i1} = K_{i2} = 1$, $T_{g1} =$

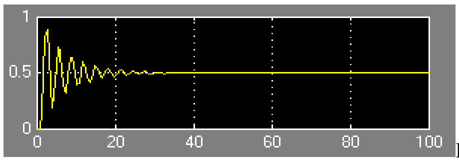
$T_{g2} = 10$

5. Case 5



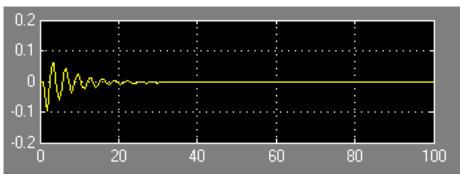
Del P dg1

Time(s)



Del P dg2

Time(s)

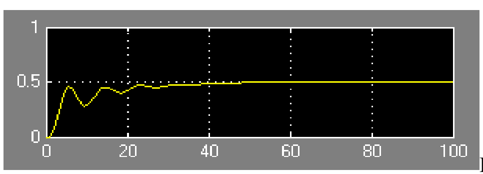


Del f

Time(s)

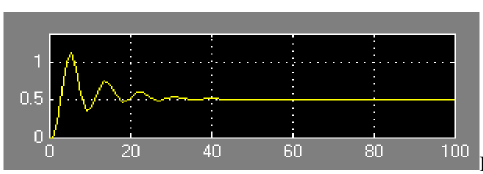
Fig: A.5.Case5: effects of the magnitude of droop constant$R_1 = R_2 = 0.01$, $K_{i1} = K_{i2} = 1$, $T_{g1} = T_{g2} =10$

6. Case 6



Del P dg1

Time(s)



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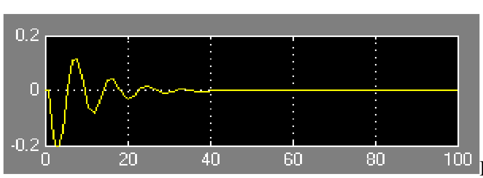
Time(s)

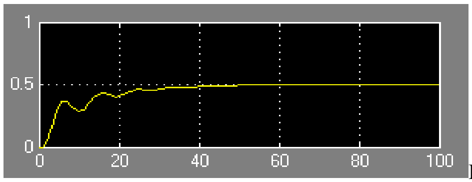


Del f

Time(s)

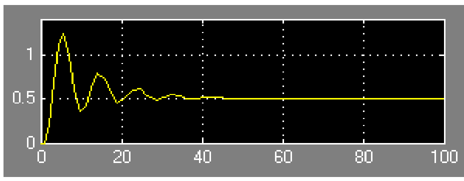
Fig: A.6.Case6: effects of droop constant between DGs, $R_1=3R_2$ ($R_2=0.05$), $K_{i1} = K_{i2} = 1$, $T_{g1} = T_{g2} = 10$

7. Case 7



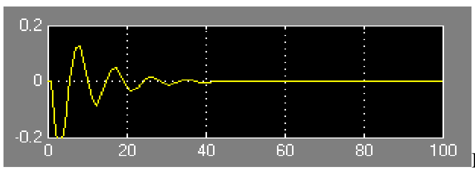
Del P dg1

Time(s)



Del P dg2

Time(s)

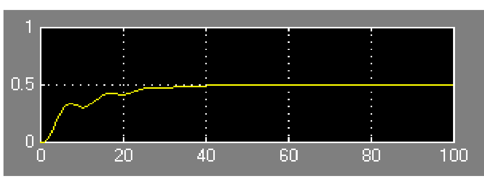


Del f

Time(s)

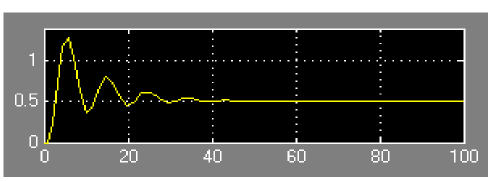
Fig: A.7.Case7: effects of droop constant between DGs, R_1=5R_2 (R_2=0.05), K_{i1} = K_{i2} = 1, T_{g1} = T_{g2} = 10

8. Case 8



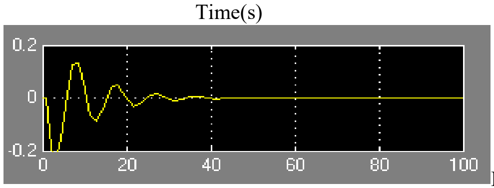
Del P dg1

Time(s)



Del P dg2

Time(s)

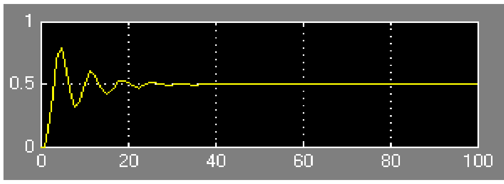


Del f

Time(s)

Fig: A.8.Case8: effects of droop constant between DGs, R1=8R_2 (R_2=0.05), K_{i1} = K_{i2} = 1, T_{g1} = T_{g2} = 10

9. Case 9



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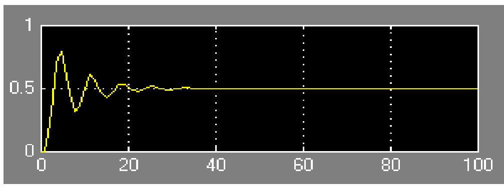
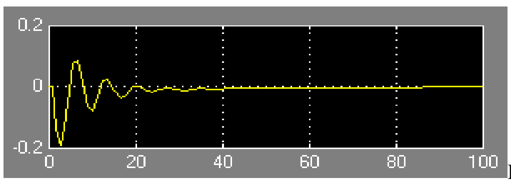
Time(s)



Del P dg2

Time(s)

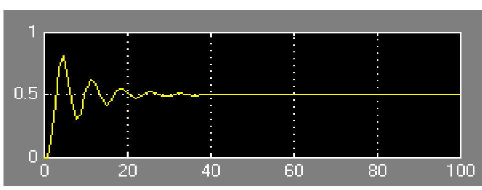


Del f

Time(s)

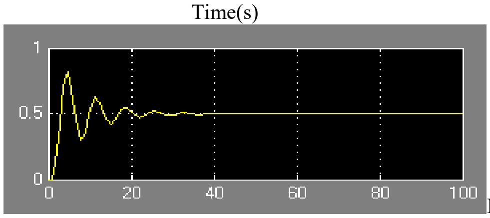
Fig: A.9.Case9: effects of the integral time constant between DGs,(K_1=K_2=0.5) (R_1=R_2=0.05) (T_{g1}=T_{g2}=10)

10. Case 10



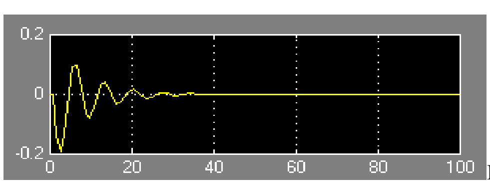
Del P dg1

Time(s)



Del P dg2

Time(s)

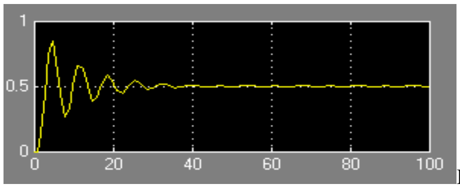


Del f

Time(s)

Fig: A .10.Case10: effects of the integral time constant between DGs , (K_1=K_2=1)(R_1=R_2=0.05)(T_{g1}=T_{g2}=10

11. Case 11



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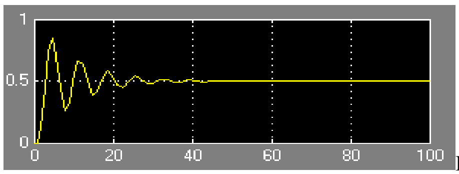
Time(s)



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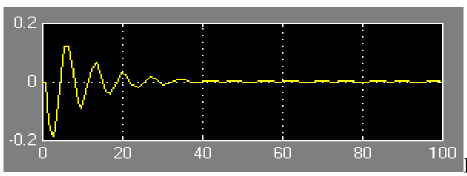
Time(s)

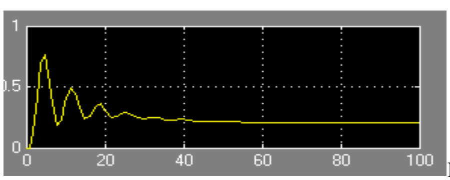


Del f

Time(s)

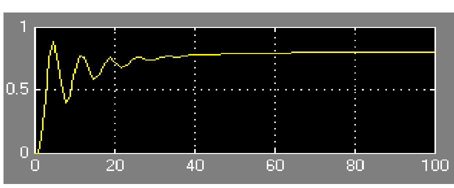
Fig: A.11. Case11: effects of the integral time constant between DGs , $(K_1=K_2=2)(R_1=R_2=0.05)(T_{g1}=T_{g2}=10)$

12. Case 12



Del P dg1

Time(s)



Del P dg2

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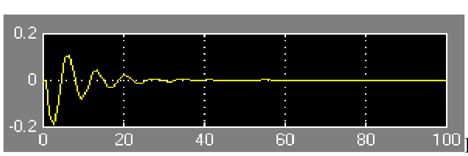
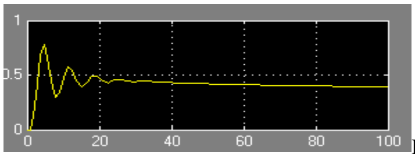


Del f

Time(s)

Fig: A.12. Case12: effects of the integral time constant between DGs, $K_1=0.5K_2=2(R_1=R_2=0.05)(T_{g1}=T_{g2}=10)$

13. Case 13



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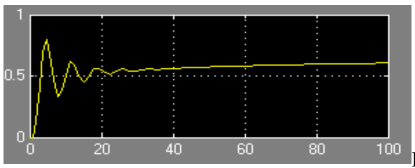

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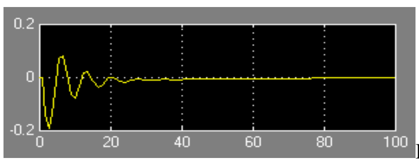
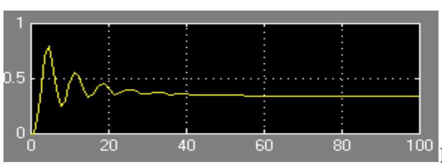


Del f

Time(s)

Fig: A.13.Case13: effects of the integral time constant between DGs, K_1=0.3K_2=0.5(R_1=R_2=0.05)(T_{g1}=T_{g2}=10)

14. Case 14



Del P dg1

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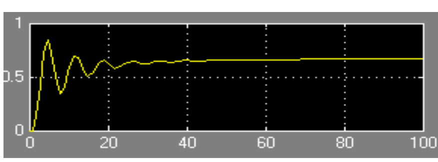

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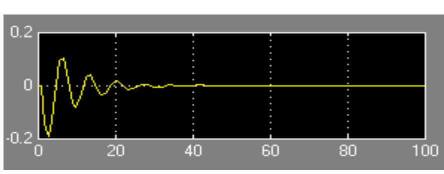
Time(s)

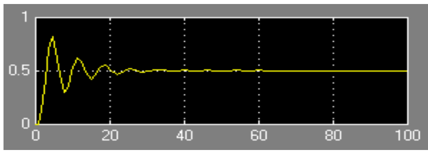


Del f

Time(s)

Fig: A.14.Case14: effects of the integral time constant between DGs, K_1=0.75K_2=1.5(R_1=R_2=0.05) (T_{g1}=T_{g2}=10)

15. Case 15



Del P dg1

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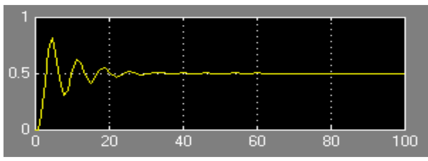
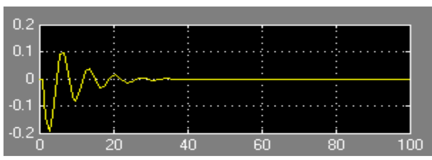


Del P dg2

Time(s)

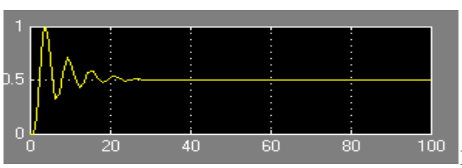


Del f

Time(s)

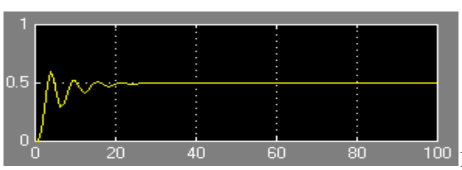
Fig: A.15.Case15: effects of the time constant Tg , (T_{g1}=T_{g2}=10) (K_1=K_2=1)(R_1=R_2=0.05)

16. Case 16



Del P dg1

Time(s)



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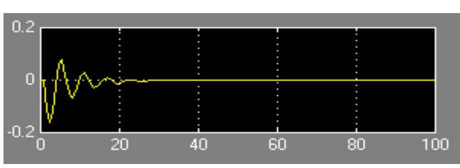
Time(s)

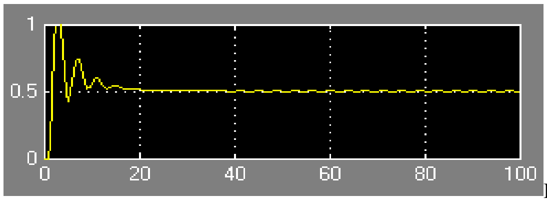


Del f

Time(s)

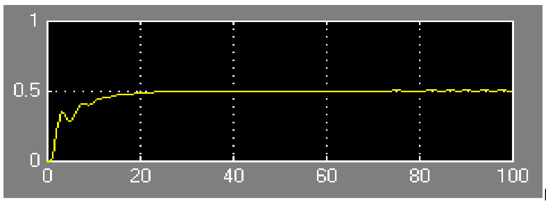
Fig: A.16.Case16: effects of the time constant T_g, (T_{g1}=5 ,T_{g2}=10) (K_1=K_2=1)(R_1=R_2=0.05)

17. Case 17



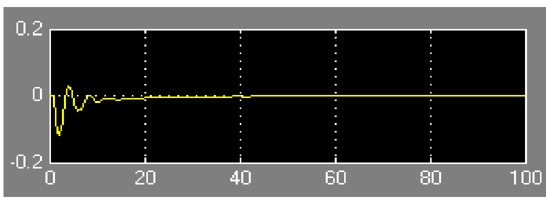
Del P dg1

Time(s)



Del Pg2

Time(s)



Del f

Time(s)

Fig: A.17 Case17 : effects of the time constant T_g , (T_{g1}=2,T_{g2}=10) (K_1=K_2=1)(R_1=R_2=0.05)