



Frequency Control of a Micro-Grid Using Demand Response and Ant Colony Method

Muhammad Anas Khan¹, Amjad Ullah Khattak²

^{1,2}Department of Electrical Engineering University of Engineering and Technology Peshawar, Pakistan
maksaddozai@gmail.com¹, amjad67@gmail.com²

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Abstract— Frequency is the most important parameter in the power system. For satisfactory operation of power system, the frequency should remain constant to its desired value. Almost all components used in the power system itself and electrical appliances are designed for a specific frequency. Some reasons of frequency deviation include: sudden load change (mismatch between supply and demand), faults and renewable energy integration in the grid system. To maintain the frequency in their desired value, traditionally generation side controllers are used. Due to their high operational cost, generation side controllers are not desirable by the power system operators. This research proposes a Demand Response (DR) technique as a promising alternate for the conventional generation controllers. It regulates the frequency by switching the responsive load ON or OFF. The proposed research operates in three different operational modes depending upon generation and load demand. Mode 1: When generation is greater than demand side load, the proposed system will switch ON the dummy load to regulate frequency, while in mode 2: Generation is less than demand side load, then the system will regulate frequency by switching OFF the non-critical load using ant colony method. In mode 3: Generation is considered to be equal to demand, in this mode there is no need to switch OFF or ON any load because frequency is already in a desired limit. By using DR program, the amount of reserved required can be reduced and hence it is more cost effective. In addition it provides a wide range of operating time frame, from a few seconds to few minutes.

Keywords— Demand Response, Frequency Control, Generation Side Controllers, Power Systems.

I. INTRODUCTION

The traditional power sector has moved towards the introduction of smart grid with the aim of developing more efficient, more reliable and cleaner electric grid. Commonly smart grid refers to electricity delivery network which improves the sustainability, efficiency, and economics of the production and distribution of electricity using the two way communication network and computer technology.

Micro grid (MG), within a smart grid network is defined as a distribution network that consists of distributed energy sources (DER) units, like solar panels, wind turbine (WT) and

diesel generator (DZ). An MG can operate in both cases, either in an islanded mode or connected to main grid using common coupling point (CCP). In an islanded mode it is totally disconnected from the main grid, while in CCP it is connected to the main grid. In islanded mode, the frequency stability is the most critical issue because there is no such connection to the main grid and inertia of this system becomes lower than that of the grid connected mode. This also effects the system frequency. For keeping the system frequency in a desired range whatever the conditions are, the supply and demand equilibrium must be followed as shown in Figure 1.

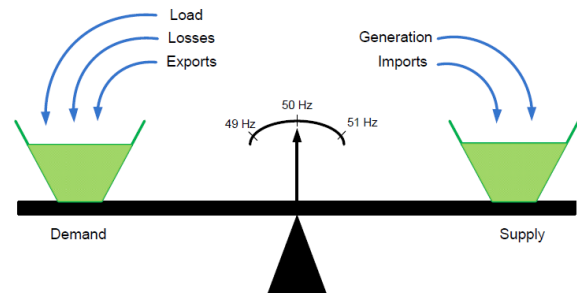


Figure 1. Supply and Demand Equilibrium

However a small disturbance happened in demand side or supply side can deviate power system frequency from its desired limit that needs to be compensated within a few seconds to maintain the power system stability. Some reasons of frequency deviation include: sudden load change (mismatch between supply and demand), faults (due to faults mismatch occurs), and renewable integration in the grid system (due to their stochastic nature, they are unpredictable) [1]. To maintain frequency stability, traditionally generation side controllers (as a spinning reserve) are used to maintain balance between energy supplied and load demand gap. These traditional generation side controllers have two main level controllers named as primary and secondary frequency controller. Primary frequency control restores the balance between generation and load within seconds, it is also called a local automatic controller. Here it is important to mention that primary controller is not much capable to return back the frequency to its desired limit, however it restricts the frequency from further drop and help in stabilizing it. Secondary frequency control is

used to bring the frequency back to its desired value. The response time of both controllers should be taken into account. The secondary control action time is 30 seconds up to few minutes while the response time of primary frequency control is much shorter as compared to secondary, so the devices used in primary control must act very fast. These traditional generation side controllers add very high operation cost in the power system that is not desirable by the power system operator. High operation cost of traditional controllers and introduction of smart grid technology made researchers to start looking for new alternative methods. DR program within smart grid technology is considered as a promising alternate for these conventional controllers, to effectively regulate frequency by switching the responsive load ON and OFF. By using DR program, the number of reserved required can be reduced and thus it is more cost effective. Furthermore, it can act very fast and contribute in providing a wide operating range of time from a few seconds to a few minutes and also reduce CO₂ emission. In addition, DR has recently got considerable attention for its use in different purposes i.e. DR can be used in power market for economic benefit, it is also used for day-ahead scheduling and off-line planning as reported in [2]-[8]. In ancillary service market, availability of load as DR resources has been investigated in [9-11]. Although the references discussed above did not analyze DR's effect on system frequency neither any model nor strategy was discussed for transmission or distribution grid. This research presents a primary frequency control using DR strategy at the distribution side in a MG.

A. Research Problem

Frequency has much importance in the stability of power system, unstable power system increases the risk of black outs or power system outages. Frequency is mainly effected by integration of renewable energy sources (due to their stochastic nature), faults, and mismatch between supply and demand. Traditional methods for frequency control are on generation side and are very costly.

B. Objectives of Research

This research paper is aimed to achieve frequency stability based on demand response techniques. The objectives of this research paper are:

- To control and regulate the system frequency using primary frequency regulator based on DR technique.
- To make the system stable by controlling the gap between load demand and generation response.
- To achieve frequency control by making equilibrium between generation and demand.
- To suggest the technique in future which can be used for controlling the frequency practically.

II. LITERATURE REVIEW

The literature review of this research paper is divided into different parts which are explained individually.

A. Related Work to Demand Response

Y. Qing et al. [12] controlled the multi-area power system frequency using DR. They proposed a system that, control both tie-line swing and area frequency of different areas. Here two steps strategy was applied, firstly a DR strategy is proposed that adds the tie-line swing signal as a feedback in the controller which can stabilize the frequency of each area. They considered a three area power system for investigating DR strategy's effect on multi-area power system. Secondly, for enhancing the power system stability, DR is manipulated for each area. In order to control the frequency, the DR will change the switch ON/OFF. Each appliance used for DR strategy consists of two parts, an electric load and its controller. Electrical load may consists of air conditioner, a refrigerator and water cooler or heater etc. The controller can automatically switch ON and OFF the electrical load in order to control the frequency. Instead of proportional integrator (PI) controller, this DR control strategy only adopts proportional controller because it will permanently change the available DR for frequency control. In other words, we can say that if the frequency is stabilized the PI controller will not decrease power of its DR integrator to zero.

S. Ali et al. [13] performed primary frequency regulation of a micro-grid using real time central DR. They designed a demand response strategy using adaptive hill climbing (AHC) method. The AHC controller measures the frequency at the common coupling point (CCP) and used it as the input variable for the controller. If the frequency change is greater than 0.05 Hz than a percent of responsive load will turn OFF. While if the change in frequency is less than 0.05 Hz than a percent of load that is OFF will be switched ON, as shown in Figure 2. The rapid nature of AHC controller, makes it faster as compared to the speed governor of diesel generator. Since controllable load's power can be instantaneously changed from ON to OFF state depending upon the control signal they receive. Which can cause the manipulation of the responsive load at the start of disturbance (to bring the frequency within the permissible range). In order to decrease the number of manipulated load a step by step (SBS) controller is used up to where frequency is controlled. When the AHC controller control the frequency after that, SBS controller starts minimization of manipulated load up to a limit where frequency is stabilized.

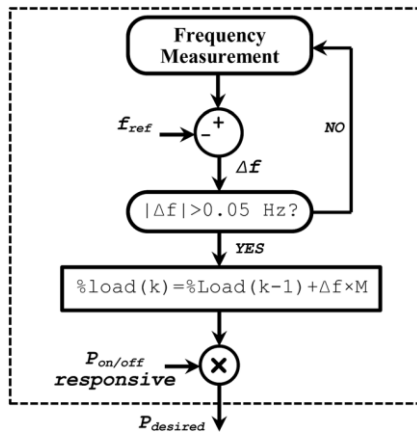


Figure 2. AHC Flow Chart

B. Related Work to Demand Side Management

P. Palensky et.al [14] gave a general overview and information about categories of Demand Side Management (DSM). According to them DSM is categorized into following categories as shown in Figure 3. In which Energy Efficiency (EE) means improving efficiency of an industrial site or building by solving hidden problems like misconfigured controls, compressed air leakage, broken equipment, dirty filters etc. Time of Use (TOU) tariff means to penalize a specified time period (i.e. 6:00-8:00 pm) for a price higher than normal hours. The customer rearrange its processes to minimize total cost of its electricity. Further DR is divided into two types. (i) Market DR which means all DR things related to market i.e. price signals, incentives, real-time pricing furthermore it depends on certain markets where prices and products are formed and traded. (ii) Physical DR is responsible for emergency signals and grid management. Spinning reserves (SR), represents the upper most (i.e. quick) category of the DSM spectrum and is implemented by loads. SR is seen as primary (active power) while secondary Control is used to restore the frequency with additional active power and grid state.

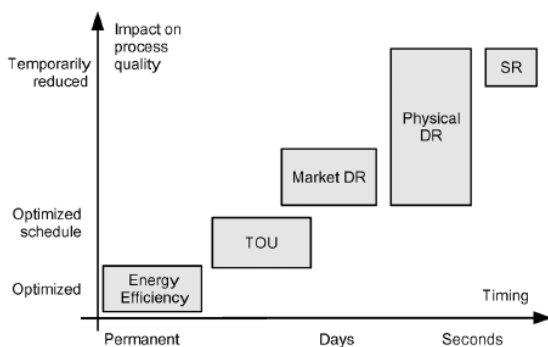


Figure 3. Categories of DSM

C. Related Work to Ant Colony Method

L. Slimani et.al [15] used ant colony optimization (ACO) method to solve the optimal power flow (OPF) problem of a medium power system. The fuel cost of thermal generating units is minimized by using ACO, for this purpose they simulate the network of 25-bus electrical network by using technique they can quickly converge to global optima. They also focused on conservation of acceptable range of generator reactive and real power outputs, transformer tapping's, bus voltage, shunt capacitances, and power flow of transmission lines.

III. METHODOLOGY

This research presents a primary frequency control at the distribution side of a MG using DR. A comprehensive DR strategy is designed in this research work which continuously tries to balance the gap between generation and demand using sliding mode control incorporated with ant colony function to regulate frequency, whether the frequency is greater or smaller than its desired limit. DR strategy used in this research is ancillary type DR in which DR events can be executed by utility company using DLC. In this way frequency is regulated by creating active power balance between generation and controllable devices. This strategy will work for electric loads such as electric water cooler or heater, air conditioning load, in short heating and cooling load physically work as a battery, because they store the energy in the form of heating and cooling. On average, residential cooling or heating loads consumption of electricity is 11% of total energy consumed which extends up to 30% during peak time [16]. The DR strategy used in this research consists of five main participants. 1. The balancing authority, which consists of frequency regulator. 2. Aggregator, which integrates or separates individual consumers. 3. Generation, is the total generated power in the MG. 4. Consumers, energy users who took part in DR program and 5. Dummy load (used to increase demand load). DR program starts by considering total generated power and total demand required for the system. Than balancing authority determines the volume of DR required accordingly. The scheduling procedure of DR is shown in Figure 4.

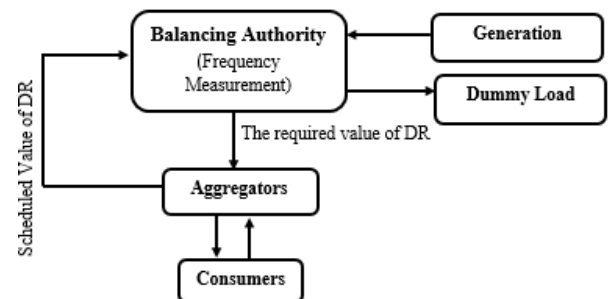


Figure 4. Scheduling Procedure of DR

A. Modes of Operation

The DR strategy used in this research paper, operates in three different operational modes, depending upon the generation and load demand.

- i. Mode 1:

In this mode, frequency increases from its desired limit and sliding mode control uses its maximum effort to bring frequency back to its desired limit.

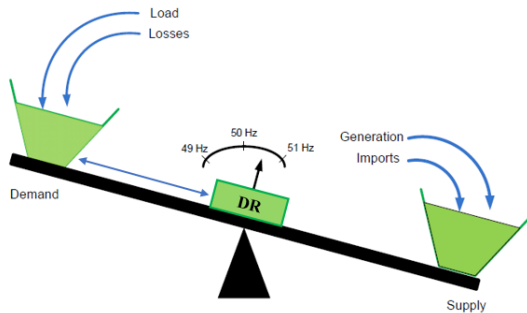


Figure 5. When Generation is greater than demand

ii. Mode 2:

In this mode, frequency decreases from its desired limit and ant colony function tries to bring back the frequency to its desired limit.

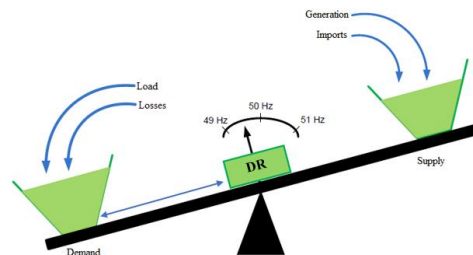


Figure 6. When Generation is less than demand

iii. Mode 3:

In this mode, no operation is done, because in this mode frequency is neither increased nor decreased from its limit.

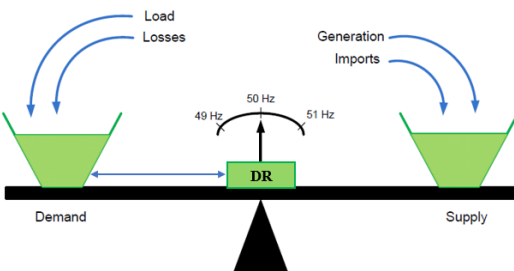


Figure 7. When Generation is equal to demand

IV. SOFTWARE MODELLING

In order to keep the frequency in its desired limit and verification of results for the sack of this, a MG model is designed in a Simulink-MATLAB software with two different controllers i.e. SMC (Sliding Mode Controller) with ant colony function and PID (Proportional Integral and Derivative) with ant colony function. It consists of different blocks i.e. Grid, three phase circuit breakers, three phase loads, three phase secondary load also known as dummy load, frequency regulator (consists of frequency measuring and controlling devices) and scopes for displaying results etc.

These blocks are connected with each other in a proper manner for getting desired results, as shown in the Figure 8. The loads are further categorized as main load, non-critical and critical load. In the Simulink model the grid consists of generating plant and is connected to the different loads i.e. Main load, non-critical load and critical load. The main load is connected to the system for the whole time while non-critical and critical load can be disconnected or connected to the system through circuit breaker on the command of frequency regulator. Beside this, a dummy load also known as secondary load is also connected to the grid.

The frequency controller will act when the imbalances occur between the power generated by the synchronous generator and different consumer load i.e. when the consumer load is greater than the generated power the frequency controller will remove the non-critical load using circuit breaker. While, the frequency controller adds the dummy load when the consumer load is less than the generation, as a result frequency will be regulated.

The DR scheduling unit is designed in Simulink-MATLAB which comprises of, frequency measuring device, aggregator, and a controller which takes decision on the basis of change in frequency. If the change in frequency is greater than ± 0.005 Hz, it will switch ON or OFF the peak load or connect the dump load to the system. The controller is deigned on the basis of Sliding mode control technique. Further another ant colony optimization (ACO) [17] function will also be incorporated with controller for optimization and switching of non-critical load. The controller will decide that which load should be switched on first preference and which is to be on second. The schematic diagram of software model is shown in Figure 8.

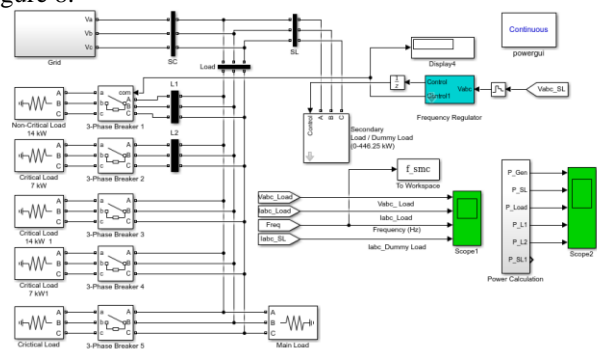


Figure 8. Software Model

A. Frequency Regulator

Frequency regulator with SMC and PID is used to control the frequency of the system and its model is shown in Figure 9. It consists of different blocks i.e. PLL (Phase log loop), dead band, discrete time integrator, Sliding mode control, pulse decoder, sampling system and Ant colony function. The frequency regulator starts with measuring frequency using PLL, after measuring the frequency, the frequency regulator compares it with reference frequency. Than the measured frequency signal is passed through dead band zone for upper and lower limit definition, after that discrete time integrator is used for filtering of the input error of signal. Than the purified

signal is passed through SMC which decides for the switching of load on the basis of error or deviation in frequency. As the output of the SMC is in analog form, for converting it into digital pulse decoder is used and at last sampling system is used for switching 8 bit load. Furthermore Ant colony function is also incorporated for switching OFF of non-critical load when generation is less than demand.

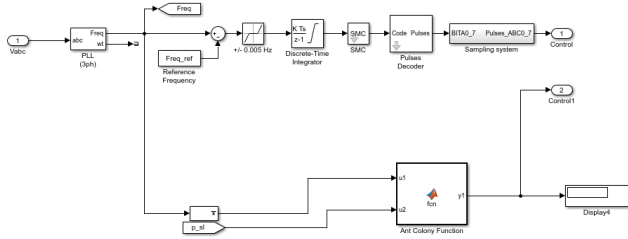


Figure 9. Frequency Regulator

V. RESULTS

In order to, keep the frequency constant (50Hz), the generation and demand must be equal. In this research work the demand side load is adjusted according to the given generation using SMC incorporated with ant colony function. For balancing the load at fixed generated power non-critical load is disconnected from the system when the generation is lower than the demand, however the dummy load is connected to the system whenever the generation is higher than demand side load.

In this research work the idea of frequency control using DR is implemented in a Simulink- MATLAB software. The results of this research work are also verified by comparing them with PID controller incorporated with ant colony function. The results achieved from the software model designed in Simulink-MATLAB software are satisfying the research idea and are explained below.

In order to fix the frequency at 50Hz, this research work is executed in three different modes. In mode 1, the generation is greater than demand side load while in mode 2, the generation is lower than the demand side load. In the last mode 3, the generation and demand side load are equal. The result of each mode are in detail discussed below.

A. Results of Mode 1

In mode 1, the generated power is considered too be greater than demand side load, due to which the frequency of the system is increased from its desired value. In order to bring back the frequency to its desired limit, the proposed system will add extra dummy load to the system. Due to the addition of dummy load the demand side load is increased and it becomes equal to the generated power. As a result a balance is occurred between demand side load and generation. The result of this mode is also verified using PID controller. Figure 10 shows the result of frequency of both SMC and PID controller.

It is clearly seen in the Figure 10 that initially the generator frequency of both controllers is fluctuating for some time and both the controller tries to set the system frequency at their desired value within a few seconds. But the response time of SMC is far better than PID controller.

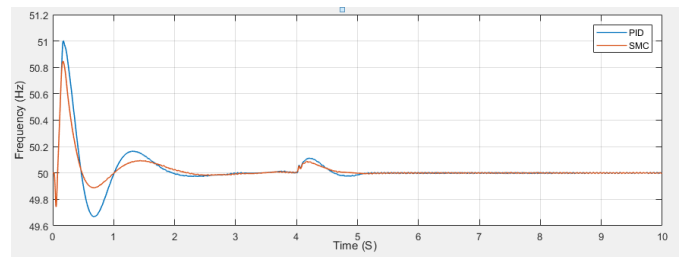


Figure 10. Generator Frequency

After 4 seconds a 7 KW load is disconnected from the system with the help of circuit breaker which can be seen in consumer load current graph in Figure 11 that it is decreased to some extent. The decrease in consumer load current means that the demand side load is now less than the generation, so the generator frequency also increases to some extent which can be seen in generator frequency graph in Figure 10.

So in order to bring back the generator frequency to its desired limit, system algorithm will add some dummy load, which can be seen in dummy load current graph in Figure 12.

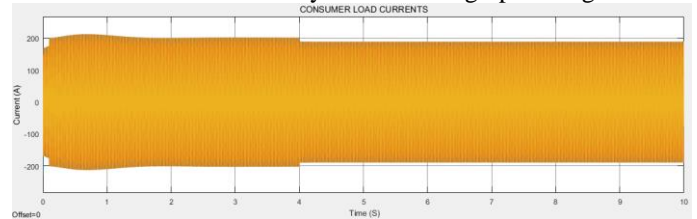


Figure 11. Consumer Load Current

That after 4 seconds dummy load current graph is increased to add some extra load in the system to create a balance between generated power and demand side load, as a result frequency becomes equal to the required limit i.e. 50Hz.

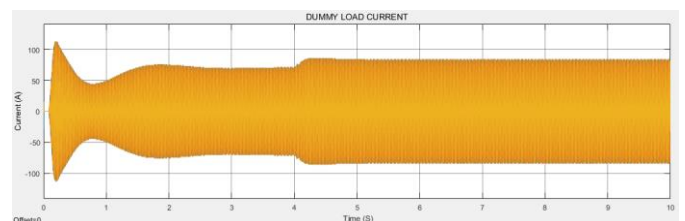


Figure 12. Dummy Load Current

Figure 13 Shows the graph value of total generated power for mode 1. In this figure a small transient can also be seen at 4 seconds because at that time a 7 KW load is switched ON.

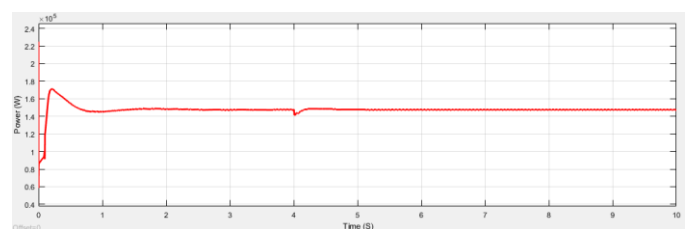


Figure 13. Total Generated Power

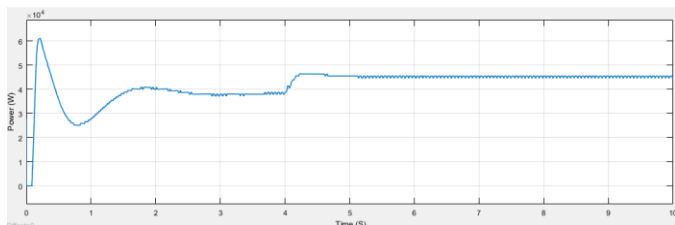


Figure 14. Dummy Load Power

In Figure 14 it is clearly seen that dummy load is initially fluctuating for a few seconds as frequency is also fluctuating, but at near to 2 seconds it became almost stable because frequency is also stable at that time. Then at 4 seconds a 7 KW load is disconnected from the system which increased the generated power as well frequency of the system, so in order to create a balance between generation and demand, dummy load is added to system in accordance to the generated power. It can also be seen in Figure 14 that the dummy load power is increased after 4 seconds.

As in mode 1 generation is greater than demand, so there is no need for switching OFF the non-critical load with the help of ant colony function, which can also be seen in Figure 15. In this figure it can be clearly observed that non-critical load is continuously connected to the system.

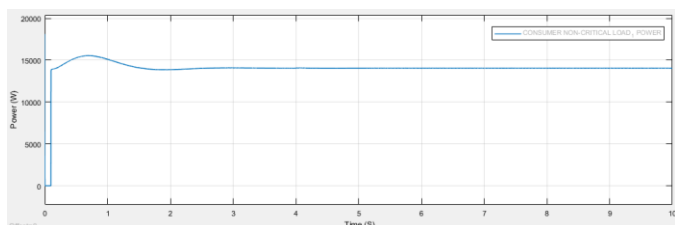


Figure 15. Non-Critical Load

TABLE I. SOFTWARE MODEL PARAMETERS FOR MODE 1

Generator Parameter	
Generator Power	150 KVA
L-L Voltage	440 V
Generator Frequency	50 Hz
Reactance of d-axis ($X_d, X_{d'}, X_{d''}$)	2.24,0.17,0.12 p.u.
Reactance of q-axis ($X_q, X_{q'}, X_{q''}$)	1.02,0.13,0.08 p.u.
Coefficient of Inertia	1 sec
Load Parameter	
Total Connected Load	109 KW
Main Load	60 KW
Critical Load	35 KW
Non-critical Load	14 KW
Controller Parameter	
Regulator gain [K_p, K_I, K_D]	255, 0.1, 70
Signum function gain (C)	0.3

B. Result of Mode 2

When the demand side load is greater than generation side, frequency will be decreased. In order to bring back the frequency to its specified limit i.e. 50Hz, the system will remove non-critical load using ant colony function. Due to removal of non-critical load the demand side load will be equal to the generation, as a result the desired value of frequency will be achieved as shown in Figure 16 from 3 to 5 seconds but in 5 – 7 seconds a 7 KW load is connected to the system which again decreased the frequency. This decreased in frequency is immediately overcome by SMC while PID controller did not attain the frequency stability.

Consumer load current graph is shown in Figure 17. In this graph it can be clearly seen that upon decrease in frequency ant colony function immediately switched OFF the non-critical load in order to balance generation and demand. Then in period between 5-7 seconds a 7 KW load is switched ON and again frequency decreases to some extent for few microseconds between 5-6 seconds. When this 7 KW load is switched OFF, frequency of systems increases for few microsecond and system tries to switch ON its non-critical load once again.

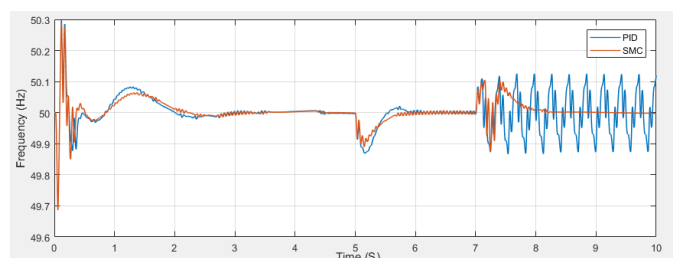


Figure 16. Generator Frequency

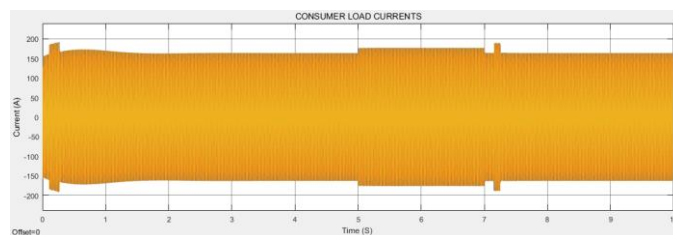


Figure 17. Consumer Load Current

Figure 18 shows the dummy load current graph. It clearly shows that before the closing of non-critical load, the dummy load approached to zero in between 0-1 second. After switching OFF non-critical load dummy load is switched ON to some extent for creating balance between generation and demand.

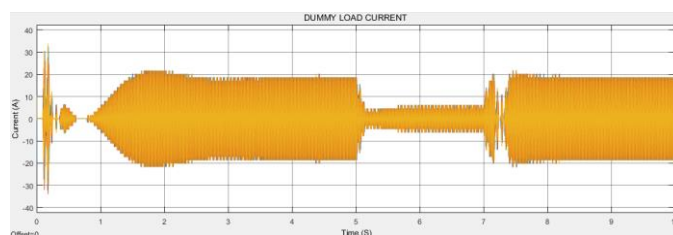


Figure 18. Dummy Load Current

Figure 19. Shows the graph value of total generated power for mode 2. In this figure a huge transient can be seen at starting few microseconds because of mismatch between generation and demand. By disconnecting the non-critical load a balance is created between generation and demand. After few seconds two more transients can be seen at 5 and 7 seconds because of switching OFF and ON a 7 KW load. In this mode generation is set at 100 KVA and demand load is 109 KW which creates an imbalance between generation and demand that's why frequency starts to decrease in starting few seconds.

To overcome this imbalance ant colony function switched OFF the non-critical load of 14 KW to regulate the frequency to its desired value. It can be clearly seen in Figure 20 that consumer non-critical load is switched off after 0.25 seconds. System tried to switch ON the non-critical load once again at 7 seconds but failed because generation is still less than demand. In Figure 21 dummy load power graph is shown. After disconnecting non-critical load generation remains the same of 100 KVA but demand load side load is decreased up to 95 KW. This difference between generation and demand is fulfilled by dummy load, which can also be seen in dummy load graph.

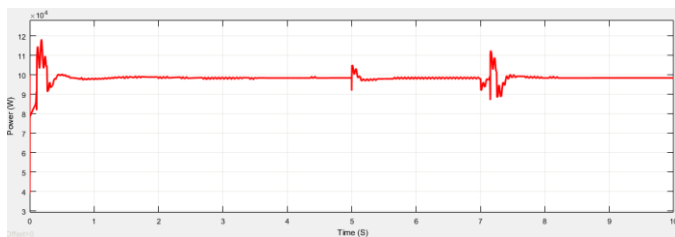


Figure 19. Total Generated Power

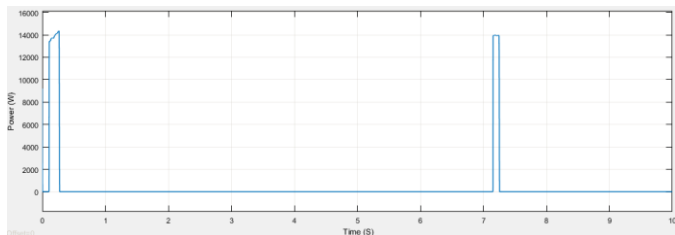


Figure 20. Non-Critical Load Power

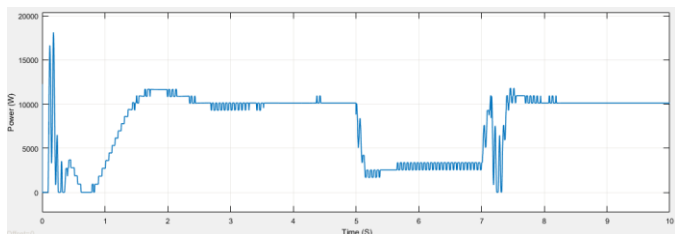


Figure 21. Dummy Load Power

TABLE II. SOFTWARE MODEL PARAMETERS FOR MODE 2

Generator Parameter	
Generator Power	100 KVA
L-L Voltage	440 V

Generator Frequency	50 Hz
Reactance of d-axis ($X_d, X_{d'}, X_{d''}$)	2.24,0.17,0.12 p.u.
Reactance of q-axis ($X_q, X_{q'}, X_{q''}$)	1.02,0.13,0.08 p.u.
Coefficient of Inertia	1 sec
Load Parameter	
Total Connected Load	109 KW
Main Load	60 KW
Critical Load	35 KW
Non-critical Load	14 KW
Controller Parameter	
Regulator gain [K_p, K_i, K_d]	255, 0.1, 70
Signum function gain (C)	0.3

C. Result of Mode 3

When the generation and demand side load are equal. It means that frequency of the system is in its desired limit, there is no need for switch ON or OFF of any load. The frequency comparison of mode 3 is shown in Figure 22.

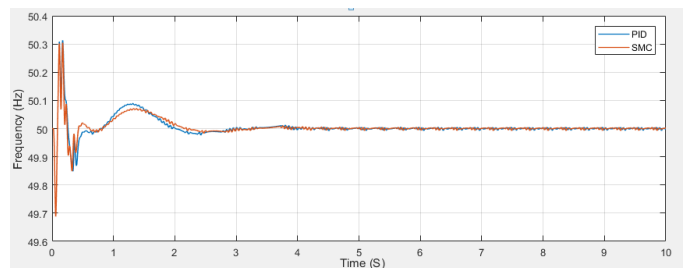


Figure 22. Generator Frequency

In this figure it is clearly seen that, results of both controllers are almost same. In this mode there will be no switching of load either critical or main load. Figure 23 shows the dummy load current graph. In this graph it is clearly seen that after few fluctuation in dummy load current graph, it has constant dummy load current.

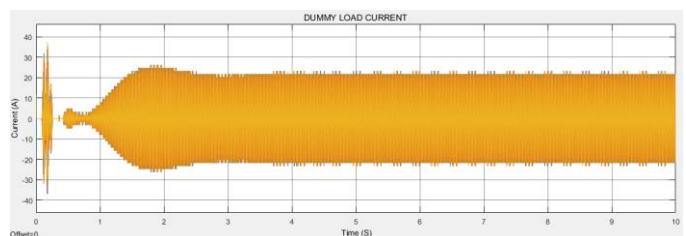


Figure 23. Dummy Load Current

In this mode generation is set at 109 KVA as shown in Figure 24 and demand load is 109 KW also increasing because of system losses as shown in Figure 25, which creates a small imbalance between generation and demand because of

generation KVA rating as well as generator reactance and other losses.

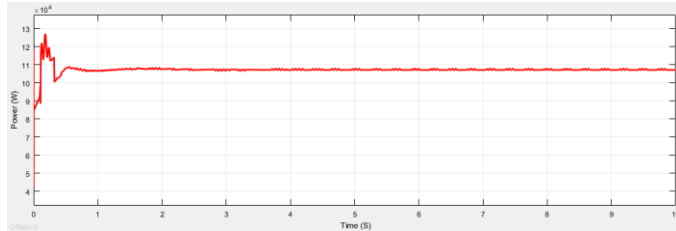


Figure 24. Generated Power

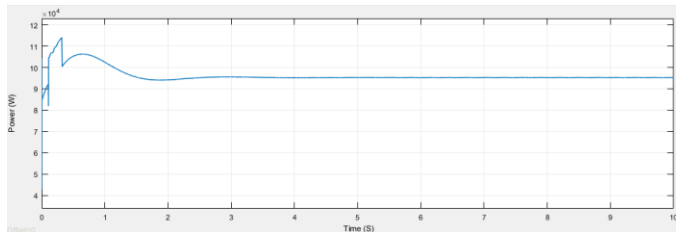


Figure 25. Total Demand Load

That's why frequency starts to decrease in starting few micro-seconds. To overcome this imbalance ant colony function switched OFF the non-critical load of 14 KW as shown in Figure 26 to regulate the frequency to its desired value. After switching the non-critical load there is approximately 12 KW extra generation in the system which is balanced by switching 12 KW dummy load ON to increase the system demand as shown in Figure 27.

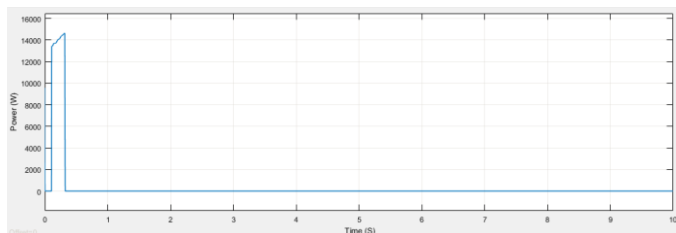


Figure 26. Non-Critical Load

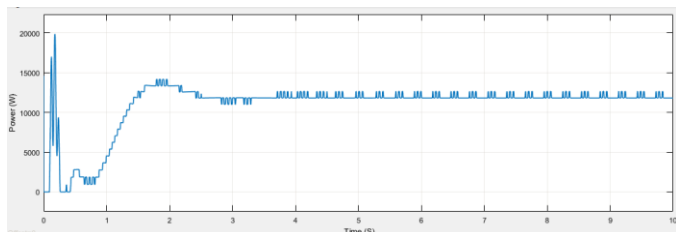


Figure 27. Dummy Load Power

TABLE III. SOFTWARE MODEL PARAMETERS FOR MODE 3

Generator Parameter	
Generator Power	109 KVA
L-L Voltage	440 V
Generator Frequency	50 Hz

Reactance of d-axis ($X_d, X_{d'}, X_{d''}$)	2.24,0.17,0.12 p.u.
Reactance of q-axis ($X_q, X_{q'}, X_{q''}$)	1.02,0.13,0.08 p.u.
Coefficient of Inertia	1 sec
Load Parameter	
Total Connected Load	109 KW
Main Load	60 KW
Critical Load	35 KW
Non-critical Load	14 KW
Controller Parameter	
Regulator gain [K_p, K_I, K_D]	255, 0.1, 70
Signum function gain (C)	0.3

CONCUSLION

It is concluded that, frequency is the most important parameter in the power system. Almost all components used in the power system itself and electrical appliances are designed for a specific frequency. A small variation in frequency can cause an electrical appliance to diverge from its desired output. Therefore, it is very important to keep the frequency within a specified limit. In order, to keep the frequency within, its desired limit the proposed system used demand response technique to regulate the frequency of the power system. With the help of this system frequency can be easily regulated using demand side, instead of traditional generation side methods.

The proposed system continuously measures the frequency of the system, if any abnormality in the system frequency is found, the proposed system will act accordingly. The proposed system will operate in three different modes. In mode 1: The generation is greater than demand side load, frequency is increased, so in order to stable the system frequency, the proposed system adds dummy load to the system. However, in mode 2: The generation is less than demand side load, frequency is decreased from its desired limit, and to bring back the frequency within the desired limit the proposed system disconnects the non-critical load using ant colony function. Moreover in mode 3: The generation is equal to the demand side load, frequency will be in desired limit and proposed system neither adds nor remove any load to and from the system.

FUTURE WORK

The purpose of this research is to regulate the power system frequency using demand response technique. In future this proposed system can be practically implemented for the controlling of frequency in the power system i.e. renewable energy systems, non-renewable energy systems and etc.

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Muhammad Anas Khan received the B.Sc degree with distinction from CECOS University Peshawar, Pakistan and M.S degree from UET Peshawar Pakistan. His research include Smart Grid, Demand Response, Frequency Control, IoT based Power System Management.

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