OPTIMAL LOAD SHEDDING SCHEME

IN WIDE AREA NETWORK

A Thesis Submitted in partial fulfilment

of the requirements for the award of the degrees

BACHELOR OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

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MASTER OF TECHNOLOGY

in

COMMUNICATION SYSTEMS

By

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CERTIFICATE

This is to certify that the project report entitled **"Optimal Load Shedding Scheme in Wide Area Network"** submitted by **Mr. Saptarshi Prakash (EE09B076)** is a bonafide record of work carried out by him at Power Systems Laboratory, Department of Electrical Engineering, Indian Institute of Technology Madras, in partial fulfilment for the award of degrees, **BACHELOR OF TECHNOLOGY** in Electrical Engineering and **MASTER OF TECHNOLOGY** in Communication Systems. The contents of this report have not been submitted and will not be submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

With the increase in the number of consumers, the electrical demand in the distribution level of Micro Grids is also increasing day by day. Hence, the number of Micro Grids in the electric power system is increasing rapidly to meet this increased electrical demand.

One common disturbance is the imbalance between generation and load due to an overload situation caused by generator outage or loss of transmission lines. Safe operation of a power system will require that system frequency is kept within a specified range. When the generation is insufficient due to disturbances, the frequency might fall under the minimum allowable value which may lead to system blackout if not property counteracted. The system spinning reserve can compensate small overload, whereas large one requires rapid emergency control actions to be taken by under frequency load shedding schemes. Load Shedding Schemes trip certain loads temporarily in order to balance the system and consequently recover the nominal operating frequency so that the system is back into balanced state.

The focus of this project is to study the traditional Under Frequency Load Shedding Schemes (UFLS) and develop an Intelligent Load Shedding Scheme using communication techniques such as Wide Area Network.

CHAPTER 1

INTRODUCTION

1.1 Power System Stability

The property of a power system to remain in the operating equilibrium under normal operating conditions and to regain an acceptable state after a disturbance is called Power System Stability. Power System Stability is broadly classified into three types:

1. Angular Stability
2. Voltage Stability
3. Frequency Stability

1.1.1 Angular Stability

Angular Stability is the ability of the synchronous machines that are connected to the network to remain in synchronism. Depending on whether the system is tested against a small or a large disturbance, angular stability can be further classified into two types, namely small signal stability and transient stability. Small signal stability indicates that the machines can remain in synchronism after a small disturbance, while small signal instability results in increasing amplitudes of electromechanical oscillations that eventually take the machines out of synchronism. Transient stability indicates that the machines can get back to a normal operating state after a large transient disturbance like a fault. Such a disturbance causes wide variations in the rotor angles. If a system is transiently unstable, the machines in the system will not be able to get back to synchronism and hence the system collapses.

1.1.2 Voltage Stability

Voltage Stability is the property by which the power system can keep the voltage magnitudes at all the buses at an acceptable level. Voltage instability is caused by lack of sufficient reactive power, which in turn is affected by the loading level on transmission lines. If the transmission lines are heavily loaded, the reactive power consumed by the line reactances is much higher and hence the voltage magnitude decreases. The relation between line loading and the voltage drop is highly non-linear. After reaching a certain point on the power-voltage curve (nose curves) called the critical voltage point at a small part of the network, the voltage suddenly drops very steeply leading to local network blackout. This phenomenon is called voltage collapse.

1.1.3 Frequency Stability

Frequency Stability is the property by which the power system can keep the operating frequency of the system at the nominal value. Unlike voltage stability, frequency stability is a global problem. Frequency stability is determined by the ability of the power system to match the total generation in the system with total loading at any point of time. When there is a mismatch, the operating frequency deviates from the nominal value. If there is excessive load, the frequency drops to a lower value and if there is excessive generation, the frequency increases to a higher value. Due to the continuously changing nature of the load, the frequency does deviate by a very small amount, but this is corrected immediately by adjusting the generation. The focus of the dissertation is frequency stability over the "medium term (10 seconds to a few minutes)" of large interconnected networks when subjected to a large disturbance.

1.2 Micro Grids

Micro Grids are modern, small-scale versions of the centralized electricity system. They are an integrated energy system intelligently managing interconnected loads and distributed energy resources and capable of operating in parallel with, or independently, from the existing utility's grid. They achieve specific local goals, such as reliability, carbon emission reduction, diversification of energy sources, and cost reduction, established by the community being served. Smart Micro Grids generate, distribute, and regulate the flow of electricity to consumers locally. Micro Grids are also an ideal way to integrate renewable resources on the community level and allow for customer participation in the electricity enterprise. The energy sources may be rotating generators or distributed energy (DE) sources directly connected to grid or interfaced by power electronic inverters. The installed DE may be wind, solar, fuel cells, geothermal, biomass, steam and gas turbines.

The connected loads may be critical or deferrable. Critical loads require reliable source of energy and demand stringent power quality. Non-critical loads may be shed during emergency situations and when required as set by the Micro Grid operating policies. The intermediate energy storage device is an inverter-interfaced battery bank, hydrogen storage, super capacitors or flywheel.

The Micro Grid can operate in grid-connected mode or in islanded mode. In grid-connected mode, the Micro Grid either draws or supplies power to the main grid. The Micro Grid components are controlled using a decentralized decision making process in order to balance demand and supply coming from the sources and the grid. The distribution system (or its sections) to which at least one distributed generation is connected forms a Micro Grid. Micro Grid concept assumes an aggregation of loads and micro source operating as a single system providing both power and heat. The point of coupling between the Micro Grid and the main grid differentiates some of the Micro Grid definitions.

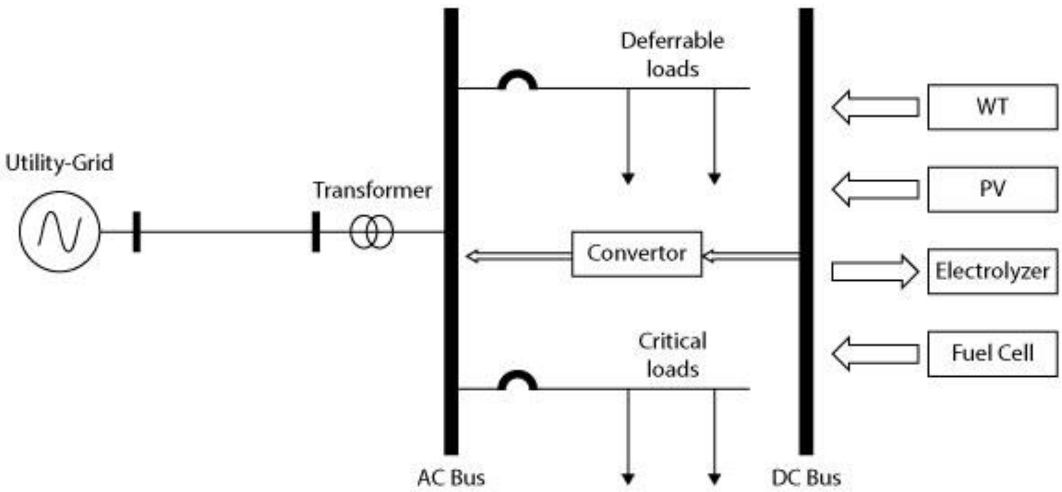

Figure 1.1: Single Line Diagram of Micro Grid

1.3 Micro Grid Classification

Micro Grids can be classifies into various types depending upon the load it supplies, and thus has characteristics of its own. Majorly it is divided into three types viz. Residential Micro Grid, Remote Area Micro Grid and Industrial Micro Grid. Differences between the above mentioned Micro Grids are shown below in Table 1.1:

Table 1.1: Comparison between different types of Micro Grids

	Residential	Remote Area	Industrial
Utility Connected	May be	No	Yes
Autonomous	May be	Yes	No
Emphasis on	Minimization of cost of supply of power	To supply power for a maximum period	Reliable power (zero load rejection) with minimum cost of operation
IRES Component	PV / Wind	PV / Wind / Hydro / Biomass	Fuel based power plants

Some publications define a Micro Grid as an intentional island, while others characterize it as operating connected to the main grid. Combining all these definitions, Micro Grids can be again categorized based on their interconnection into 3 main types:

Type 1 Micro Grids are normally connected to the main grid at a single or multiple points. In this type of Micro Grid, the distributer generations are designed to work in parallel with the main grid and shut down when the Micro Grid is isolated. With prior studies and arrangements, they can operate under an intentional islanding situation. This Micro Grid category is currently suggested by a number of interconnection guidelines.

Type 2 Micro Grids are normally isolated from the main grid and operate independently. In this case, the local distributer generations need to meet the peak demand of the Micro Grid. They are used by electrical consumers such as hospitals with backup (or emergency) generators which kick in once a power outage is sensed.

Type 3 Micro Grids can operate in both grid connected and isolated situations and switch between the two modes seamlessly. The development of this Micro Grid category utilizes communication and sophisticated control strategies to meet its objectives of power reliability and quality.

The above-mentioned definition of Micro Grids covers a large range of applications that can be divided into: institutional, commercial, industrial, community, utility, remote off-grid and military. Traditionally, power flow control mechanisms incorporate Preventive and Corrective modes. When a contingency occurs and the line power flow limit is violated, the corrective control mode is activated.

Although the risk management of power flows represents a classical power system problem, the increasing number of Micro Grids has exacerbated the problem. For example, if a distributed generator capacity surpasses the ratings of the upstream network, power flows become a risk control problem because following a contingency; the network assets may operate above their firm capacity and fail. Power flow management systems need to consider the capacity and security of the system during Normal, Emergency (after circuit outage) and Island operations. Thus, Micro Grids are operated in one of the following configurations:

1. Unit Power Control
2. Feeder Flow Control
3. Hybrid

The first scheme, which is ideal for normal conditions, sets distributed generators to generate certain amounts of power based on factors such as cost and environmental impacts. In the second scheme, Feeder Flow Control maintains the power flow so that the Micro Grid appears as a constant load from the utility point of view. The hybrid scheme combines both methods, based on the needs of the system. If the capacity of the upstream equipment is insufficient in the case of a contingency, it is referred to as a weak connection. For Micro Grids with weak links to the utility, a hybrid mechanism is recommended, as it applies the Unit Power Control under normal conditions. To deal with emergencies, i.e., when the supply lines operate at or above their transmission limits, this thesis proposes utilizing a Feeder Flow Control algorithm that combines on-line load shedding with a wind turbine supplementary controller.

CHAPTER 2

NEED FOR LOAD SHEDDING SCHEME

2.1 Power Generation in India

During the year 2010–2011, demand for electricity in India far outstripped availability, both in terms of base load energy and peak availability. Base load requirement was 861,591 GWh against availability of 788,355 GWh, a deficit of 8.5%.

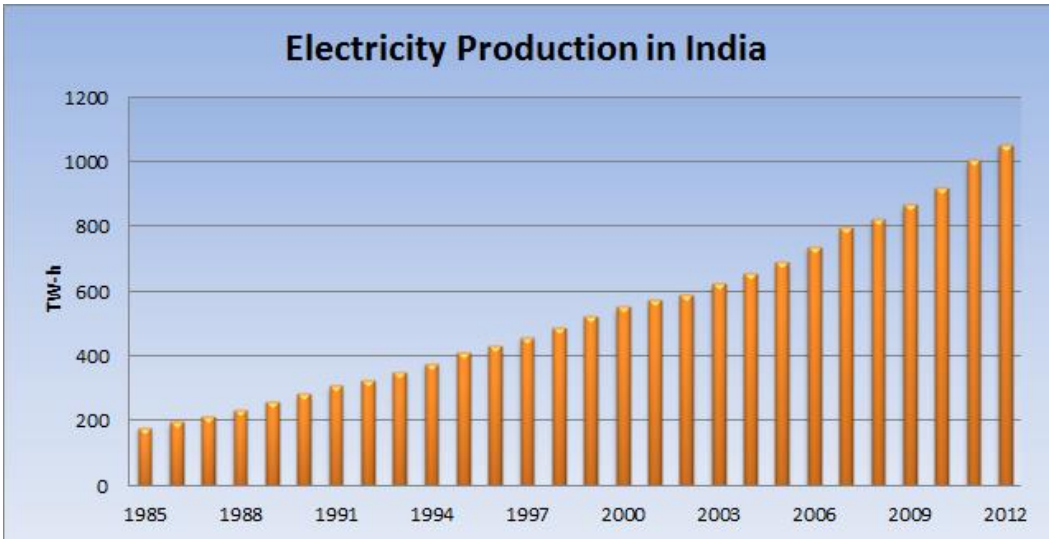

Figure 2.1: Electricity production in India
[en.wikipedia.org/wiki/File:Electricty_India_1985-2012.png]

In a May 2011 report, India's Central Electricity Authority anticipated, for 2011–2012 year, a base load energy deficit and peaking shortage to be 10.3% and 12.9% respectively. The peaking shortage would prevail in all regions of the country, varying from 5.9% in the North-Eastern region to 14.5% in the Southern Region. India also expects all regions to face energy shortage varying from 0.3% in the North-Eastern region to 11.0% in the Western region. India's Central Electricity Authority expects a surplus output in some of the states of Northern India, those with predominantly hydropower capacity, but only during the monsoon months. In these states, shortage conditions would prevail during winter season. According to this report, the five states with largest power demand and availability, as of May 2011, were Maharashtra, Andhra Pradesh, Tamil Nadu, Uttar Pradesh and Gujarat.

2.2 Energy from Renewable Sources

Economic growth, increasing prosperity and urbanization, rise in per capita consumption and spread of energy are the key factors that are responsible for substantially increasing the total demand for electricity as show in Figure 2.2 below. Thus there is an emerging energy supply-demand imbalance. Renewable energy can no longer be treated as an alternate form of energy as it is increasingly becoming a vital part of the solution to the nation's energy needs. As of 31 March 2012, installed capacity of renewable energy based power generation was 24,503 MW. The major renewable energy sources in India are wind energy, solar energy, biomass & waste energy, and small-hydro energy.

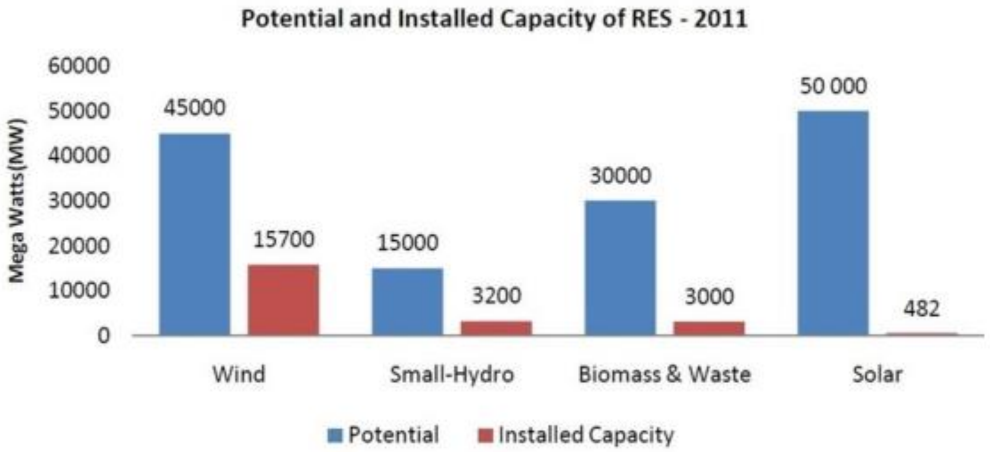

Figure 2.2: Potential and installed capacity of Renewable Sources of Energy [www.mnre.gov.in]

2.2.1 Wind Energy

Development of wind power began in the 1990's and has progressed significantly in the last few years and it accounts for 6% of India's total installed capacity. As of 31 January 2014 India's total wind power installed capacity is 20298.83 MW, mainly spread across Tamil Nadu (7162.18 MW), Gujarat (3174.58 MW), Maharashtra (3021.85 MW), Rajasthan (2684.65 MW), Karnataka (2135.50 MW).

2.2.2 Hydro Energy

Hydro power projects with station capacity of 25 MW falls under the category of small hydro power capacity (SHP). Total installed capacity of small hydro projects as on 31 January 2014, was 3774.15 MW, however the estimated potential is more than 15000 MW. Most of the latent potential is in the Himalayan states. The SHP programme is largely private driven.

2.2.3 Solar Energy

India is densely populated and has high solar insolation which makes it an ideal combination for using solar power. With about 300 clear sunny days in a year, India's theoretical solar power reception is about 5000 trillion KWh/year. The daily average solar energy incident over India varies from 4 to 7 KWh/m^2 efficiency of PV modules were as low as 10% this would still be a thousand time greater than the domestic electricity demand projected for 2015. The grid connecte solar power as of December 2010 was merely 10 MW but by July 2012 the installed grid connected photovoltaics had increased to 1040.6 MW. After realizing the potential of solar power Indian government unveiled the ambitious Jawaharlal Nehru National Solar Mission to produce 20GW of solar power by 2022.

2.2.4 Biomass and Waste energy

India's climatic conditions offer an ideal environment for biomass production. Owing to its virtues, biomass gasification can play a key role in the electrification of rural and remote communities. In spite of having a potential of over 30,000 MW of power from biomass but only 3000 MW was has been exploited leaving 90% of the potential capacity untapped.

2.3 Power System Overloading

A power system continually experiences changes in its operating state. The emergency state (overloading) may occur as a result of a sudden increase in system demand, the unexpected outage of a generator or a transmission line, or a failure in any of the system components. A sudden mismatch in the generation and demand causes a change in frequency thereby disrupting the property by which the power system can keep the operating frequency of the system at the nominal value. If there is excessive load, the frequency continues to decline rapidly and in case of excessive generation, the frequency continues to increase. If adequate control action is not taken, the wide frequency excursions would lead to subsequent tripping of all available generation within the system leading to a system blackout. Such a scenario makes it difficult to reconnect and restore the network after the outage.

2.4 Load Shedding

In order to limit the frequency deviations, loads are shed if the frequency drops below a certain value. Similarly, in over generated areas, generators are tripped on over frequency. The primary responsibility of electric grids (both large interconnected systems and Micro Grids) is to match demand and generation with the help of primary, secondary and tertiary controllers. The purpose of Load Shedding is to balance load (customer demand) and generation (power plant capacity) during a sudden drop of a generating unit.

One of the basic principles of power system operations is to balance the amount of load with the amount of generation. Alleviation of this mismatch is a global and critical problem in power system operation, hence a control action strategy is necessary to effectively reduce the line overloads to the security limits in the minimum time, by generation rescheduling and/or load shedding, neglecting the economic considerations. Load shedding is the process of removal of excess load when there is deficiency in generation, so that the mismatch is rectified. Some of the load shedding techniques like the Under Frequency and Under Voltage load shedding schemes are well established and continue to be used widely for correcting frequency and voltage changes respectively.

2.5 Need for Smarter Load Relief

Traditional/Manual load shedding systems have been designed to shed loads based on parameters like frequency and voltage magnitudes that are measured locally. When the generation and supply within an area is not balanced, the frequency deviates from the nominal value. If the area is under-generated, the frequency declines, and it increases if the area is over generated.

Thus, load shedding relays measure frequency at the local bus and if the frequency drops below a certain value, a certain fraction of load connected to the bus is dropped. If the frequency keeps dropping, greater amounts of load are dropped. In Under Frequency Load Shedding (UFLS) scheme, Frequency Trend Relays are used, if greater generation deficiencies are encountered. This value of frequency threshold and the amount of load to be shed is predetermined based on system studies. The UFLS scheme is the last resort that is employed during an emergency and its main objective is to prevent total system collapse within an area. One of the drawbacks of the UFLS scheme is that, by the time these relays operate, the area under consideration would have already been disconnected from the rest of the network. Thus the scheme does not proactively shed loads to prevent an island; it only tries to prevent further frequency decline after the area has been islanded from the rest of the network. The other drawback of the scheme is that the settings for the relays are pre-set based on exhaustive studies.

With rapid expansion of electrical networks and the continually changing nature of the grid, these settings may become less effective or even obsolete over different operating conditions. Under such situations, the quantity and location of the load being shed is not optimal, resulting in shedding more loads than actually necessary and a sub-par performance. While it may sound innocuous, such below-optimal performance has been cited as major reasons why major blackouts could not be contained. A wide range of existing schemes as well as newly proposed schemes depend on frequency or rate of change of frequency ($\frac{df}{dt}$) as a measure for determining the amount of load to be shed. Reference finds that there is very little correlation between observed frequency and the actual size of the event. The oscillatory nature of $\frac{df}{dt}$ and load sensitivity to frequency make such measurements unreliable.

2.6 Need for Faster Load Frequency Control

During the normal operation of the electrical grid, the power generated by each generator is kept at a set value, determined by a variety of factors including cost of fuel, losses in the transmission lines and congestion on the transmission corridors. In addition to meeting the actual load, some amount of generation is kept on standby as a back-up in case of a forced outage of a generator. This slack generation is called the spinning reserves. When there is a mismatch in the system with excessive load, this spinning reserves can be tapped into, for temporarily overcoming the deficit. This is achieved by a control mechanism called the Automatic Generation Control (AGC). The AGC is a widely implemented supplementary control that modifies the turbine reference point (and hence, the power output) of select generators within an area based on a change in frequency and a change in tie line values, thus rectifying the deficit and restoring area frequency.

The load shedding scheme should have a sense of the amount of load that is currently connected to the network within a given area. This knowledge is necessary to ensure that the control actions that are initiated by load shedding are effective and optimum. It should be adaptive so that the scheme can adjust itself to a wide range of operating situations. The load shedding scheme should also be able to readily incorporate the vast experience in operating the system as well as the current status of operation, for taking the best decisions for maintaining stability of the grid.

CHAPTER 3

WIDE AREA NETWORK IN POWER SYSTEM

A wide area network (WAN) is a computer network spanning regions, countries, or even the world. It is a network which are spread over a large area (i.e., any telecommunications network that links across metropolitan, regional, or international boundaries) using leased telecommunication lines. In terms of the application of computer networking protocols and concepts, it may be best to view WANs as computer networking technologies used to transmit data over long distances, and between different Local Area Networks (LANs), Metropolitan Networks (MANs) and other localised computer networking architectures. This distinction stems from the fact that common LAN technologies operating at Layer 1/2 (such as the forms of Ethernet or Wifi) are often geared towards physically localised networks, and thus cannot transmit data over tens, hundreds or even thousands of miles or kilometres. WANs do not just necessarily connect physically disparate LANs. In essence, this mode of telecommunication allows a business to effectively carry out its daily function regardless of location. The Internet can be considered a WAN as well, and is used by businesses, governments, organizations, and individuals for almost any purpose imaginable.

WANs are used to connect LANs and other types of networks together, so that users and computers in one location can communicate with users and computers in other locations. Many WANs are built for one particular organization and are private. Others, built by Internet service providers, provide connections from an organization's LAN to the Internet. WANs are often built using leased lines. At each end of the leased line, a router connects the LAN on one side with a second router within the LAN on the other. Leased lines can be very expensive. Instead of using leased lines, WANs can also be built using less costly circuit switching or packet switching methods. Network protocols including TCP/IP deliver transport and addressing functions. Protocols including Packet over SONET/SDH, MPLS, ATM and Frame relay are often used by service providers to deliver the links that are used in WANs. X.25 was an important early WAN protocol, and is often considered to be the "grandfather" of Frame Relay as many of the underlying protocols and functions of X.25 are still in use today (with upgrades) by Frame Relay.

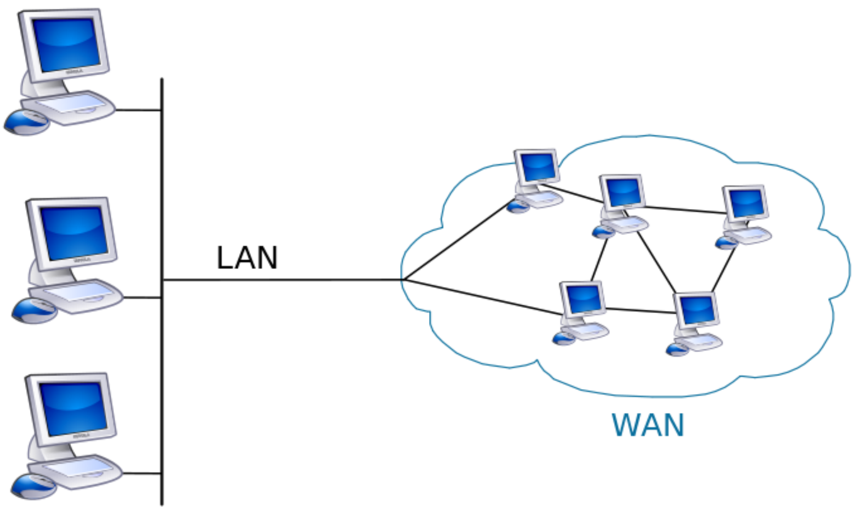

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Figure 3.1: Structure of Wide Area Network

3.1 Wide Area Network Load Shedding

To prevent a complete blackout of the Micro Grid, a fast acting and accurate load shedding scheme is required to detect the system disturbances that result in supply lines operating above their capacity and to isolate the Micro Grid from the main grid.

The scheme presented in detects the overload or trip of the supply lines, calculates the generation deficit, based on the amount of power inflow from utility and locally available power generation (reserves), and signals pre-specified interlocked load breakers to open.

Although this method is quite fast, it has many disadvantages such as: hard to change the priority of loads, no knowledge of actual demand of each feeder, shedding more loads than necessary and often shutting down the entire Micro Grid due to demand and generation mismatch. To overcome the above mentioned problems, the load shedding algorithm needs to deploy a communications network (WAN or LAN) as the backbone to convey monitoring and control data. The difference between Wide Area Networks (WAN) and Local Area Networks (LAN) platforms is their coverage. In protection particularly load shedding architectures, the LAN based system only covers inside substations, while the WAN goes beyond.

In a place like our IIT Madras Campus which is around 630 acres a WAN can cover the entire campus Micro Grid. The most common physical layer chosen for area network based systems is Ethernet, because of its predominance in the market and its low-cost implementation.

CHAPTER 4

CONVENTIONAL UNDER-FREQUENCY LOAD SHEDDING SCHEME

4.1 Under Frequency Load Shedding Scheme (UFLS)

Under Frequency Load Shedding is a method which is used when there is a decline in frequency in case of a large mismatch in load and generation. Such a mismatch occurs usually due to a forced outage of a generator or sudden increase in load. In the UFLS scheme, loads are automatically dropped when an under-frequency condition occurs. This is to avoid a total collapse of the system, otherwise known as an island-wide blackout. When the protection scheme is initiated, load is shed a block at a time isolating power delivery to predetermined areas until the power system stabilizes. Conventional UFLS system is designed to recover the balance of generation and consumption following a generator outage or sudden load increase. The loads to be shed by this system are constant load feeders and are not selected adaptively. In other words, always the same loads are dropped from the system, regardless of the location of disturbance. In this method loads are classified in three groups of non-vital, semi vital and vital loads.

Due to increasing demand for electricity, power companies need to continuously upgrade their infrastructure which often involves many years of engineering design, planning and analysis, social, economic and political negotiations, and construction.

Every load shedding table with fixed frequency technique consists of three columns: frequency threshold, load shedding block size and delay. When the supply frequency drops to one of the frequency set points, the relay timer starts counting for as long as the frequency remains below the threshold. When the time counter reaches the pre-specified time delay, the corresponding amount of load is shed.

Table 4.1: Load Shedding Plan

	Stop Frequency Drop			**Return Frequency**	
Step	**Frequency set points**	**Load blocks (%)**	**Time Delays**	**Additional load blocks**	**Time delays**
1	F1	$\Delta L1$	$\Delta t1$	$\Delta L1'$	$\Delta t1'$
2	F2	$\Delta L2$	$\Delta t2$	$\Delta L2'$	$\Delta t2'$
3	F3	$\Delta L3$	$\Delta t3$	$\Delta L3'$	$\Delta t3'$
4	F4	$\Delta L4$	$\Delta t4$	$\Delta L4'$	$\Delta t4'$
5	F5	$\Delta L5$	$\Delta t5$	$\Delta L5'$	$\Delta t5'$

$$\Delta L1=\Delta L2=\Delta L3=\Delta L4=\Delta L5$$

$$\Delta t1=\Delta t2=\Delta t3=\Delta t4=\Delta t5$$

Load shedding schedules usually have 3-5 steps with frequency difference of 0.2-0.5 Hz. Once the maximum probable overload and the number of frequency levels are determined, the size of the load shedding steps is calculated by dividing these two quantities.

Although some load shedding plans use unequal steps by shedding larger load blocks at the beginning and reducing the step size at lower frequency set points, both plans accomplish similar results. Similarly, the delay steps are equal. If, after a load shedding that corresponds to a specific level, the frequency remains below the set point, some utilities shed additional loads automatically. In many cases, the first time delay is instantaneous to stop the frequency decay without any intentional time delay, while the subsequent time delays are larger.

4.2 Example: 6-Stage vs 11-Stage

We consider an example of a 6-Stage and 11-Stage conventional UFLS scheme

Table 4.2: 6-Stage UFLS Scheme

Stage	**1**	**2**	**3**	**4**	**5**	**6**
Freq (Hz)	49.5	49.3	49.1	49.0	48.8	48.5
Load (MW)	300	400	Supply Board Trip Out	600	600	800

Table 4.3: 11-Stage UFLS Scheme

Stage	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Freq (Hz)	49.5	49.4	49.3	49.2	49.1	49.0	48.9	48.8	48.7	48.6	48.5
Load (MW)	300	200	200	200	200	200	300	300	200	300	300

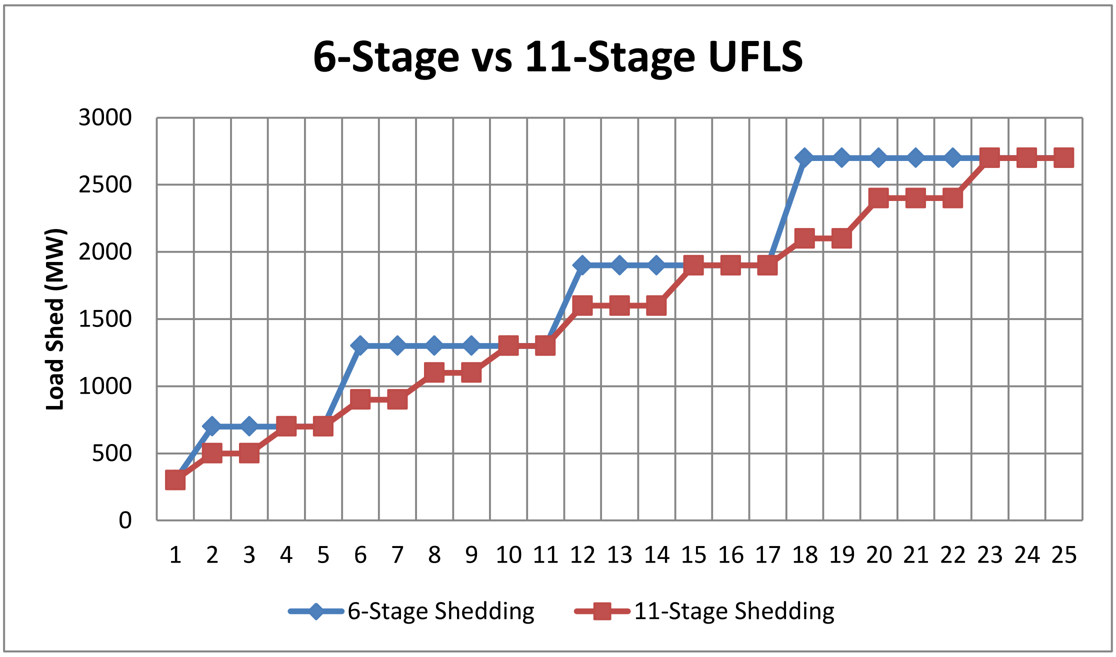


Figure 4.1: Comparison of 6-Stage and 11-Stage UFLS

The effect of minimizing over-shedding is illustrated in Figure 5.1 where the percentages of over-shedding for both schemes are compared. It shows the results of static analysis for the 25 scenarios. In the first scenario, a 300 MW generation deficiency is considered. Further l00 MW generation loss is added for the subsequent scenario. The over-shed percentage is defined as the ratio of actual amount of load shed to the amount of generation loss. Out of the 25 scenarios, the 11-stage scheme shed lesser load in 14 scenarios. Hence, as a rule of thumb, it is always better to have more stages with smaller load at each stage, to minimize over shedding. Moreover, tripping a big block of load at one time will give a large impact to an already weakened system.

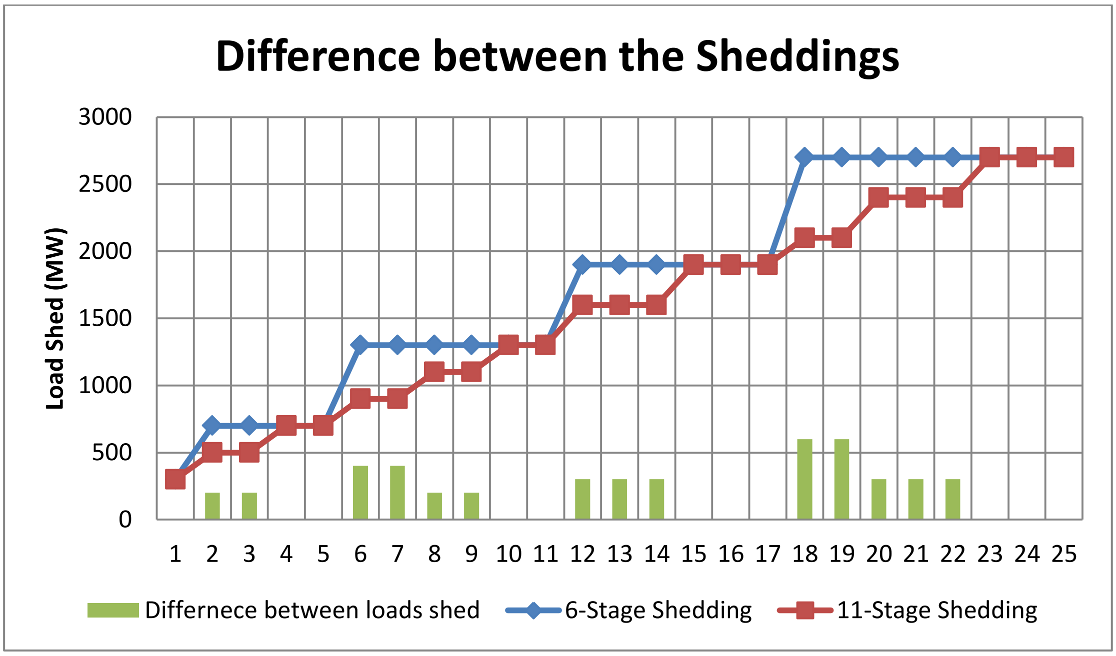


Figure 4.2: Difference between the loads shed in both the schemes

It is observed that with lower number of stages (6-Stages) and larger chunks of shedding loads, more loads are shed than required. This can be further optimized by using 11-Stages and smaller chunks of shedding loads.

CHAPTER 5

INTELLIGENT LOAD SHEDDING SCHEME

5.1 Intelligent and Adaptive Load Shedding Scheme

The conventional methods which are used for system load shedding are inefficient and they fail to calculate the correct amount of load to be shed. This is because the system loading may shift and the load may vary, i.e. the loads are not constant. This makes it difficult to predict how much load should be shed at a specific time and location.

In case of distributed generation connection where there are different power generation, the results are either excessive or insufficient load shedding. Load shedding systems with conventional under-frequency relays will be inadequate for their operation. Hence, a real time, adaptive and intelligent load shedding scheme is needed. For the design of an adaptive load shedding scheme, the following problems must be considered.

1. Estimation of the magnitude of the disturbance

2. Location of disconnection

3. Control action taken by individual relays

The actual demands of each load block are communicated through an Intelligent Electronic Device (IED). All IEDs are grouped based on their geographical location or circuit number, and each group reports to a Data Interface Unit (DIU) which is a gateway to send the demand information to the Load Shedding Manager (LSM) and to transmit commands back from LSM to circuit breakers of load blocks. All the power backup sources; Diesel Generators, Renewable sources of Energy etc. are connected to the IED Groups. The IEDs collect the metered data from local DGs and utility supply lines and send it to the LSM. Based on these measurements, the LSM detects that the utility lines are overloaded and decides how much load shedding is required. The interruption of a utility breaker is an immediate trigger of load shedding.

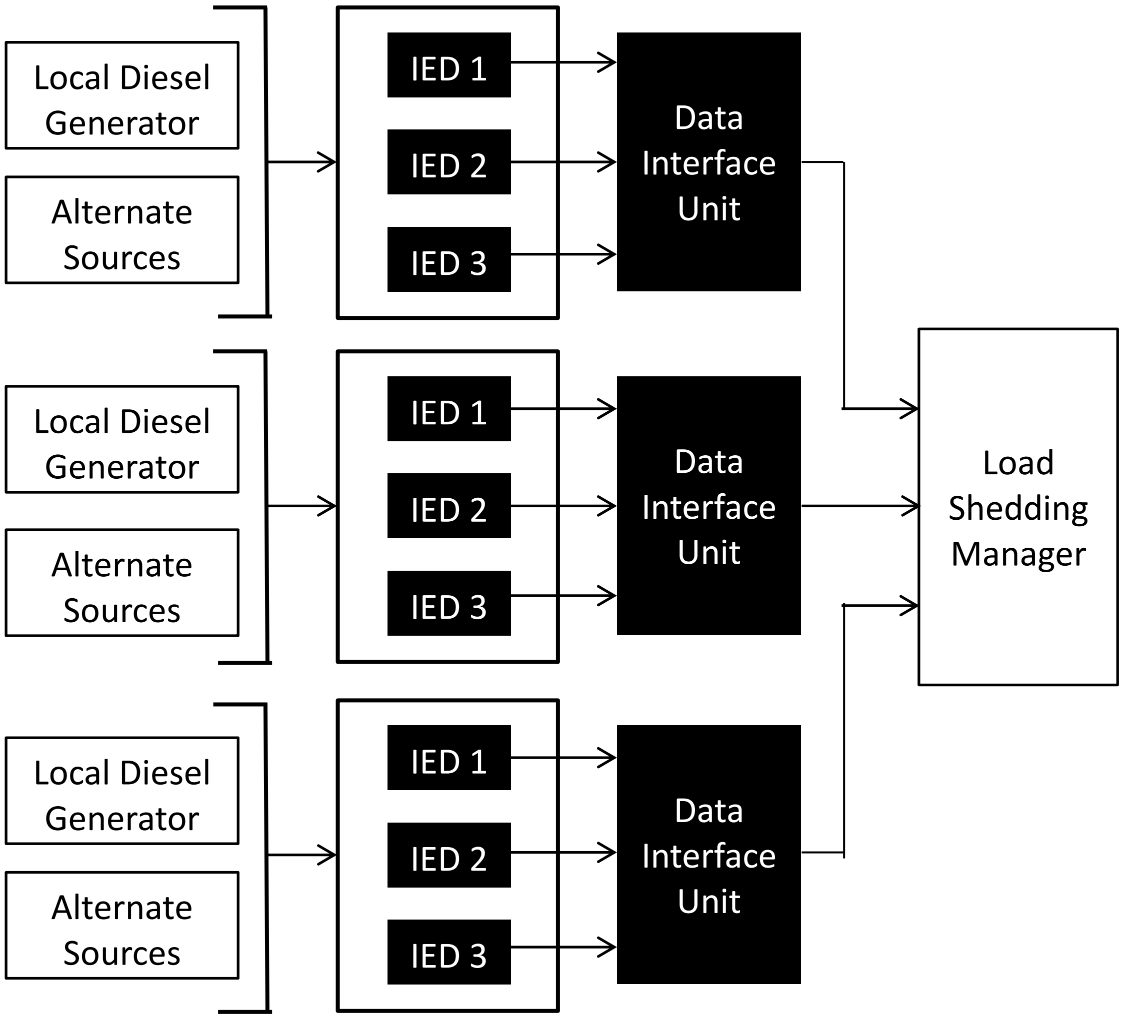


Figure 5.1: Load Shedding Block Diagram

5.2 Fault in a line

Let us assume there are there are n supply lines, L_1, L_2, L_3 …. L_n. When r number of lines trip, Load Shedding Manager calculates how much the remaining (n−r) lines are overloaded by subtracting the capacities of connected lines from the total power delivered

$$\{P_T - (P_{C1}, P_{C2}, P_{C3} \dots P_{C(n-r)})\}$$

High priority loads cannot be tripped; hence in a general situation, the condition for load shedding is,

$$\{P_T - (w \times \sum_{n=1}^{total\ lines} P_{Cn})\} \leq P_{Fixed} + \sum_{m=1}^{total\ no.\ of\ other\ loads} P_{Lm}$$

Where,

P_T : $Power\ delivered\ through\ the\ utility\ transmission\ lines$

P_{Cn} : $Total\ power\ capacity\ of\ the\ lines\ that\ remain\ connected$

P_{Lm} : $Power\ demand\ of\ each\ load\ block$

P_{Fixed} : $High\ priority\ loads\ which\ cannot\ be\ shed$

w : $1, when\ line\ is\ connected;\ 0, otherwise$

n : $Total\ number\ of\ lines\ connected$

m : $Total\ number\ of\ loads\ connected$

Although in the transition from a normal condition to and emergency situation or islanding, the LSM does not require information about the local generation and demand to calculate the amount of load shedding, this information is important during islanding operations:

$$P_L = \sum_{m=1}^{total\ no.\ of\ loads} P_{Lm}$$

$$(P_{BM} + P_{WT} - P_L) \leq \sum_{m=1}^{\substack{until\ condition\ is\ met \\ m \leq total\ no.\ of\ loads}} P_{Lm}$$

Where,

P_{WT} , P_{BM}: Wind and biomass generated power

P_L: Total load demand

m: Load meter number

P_{Lm}: Demand of each load block

5.3 Formulation

After measuring the frequency at each generator in the power system, the rate of frequency decline of each generator is determined by taking the mean of atleast 3 stages of frequency measurements.

Once the rate of change of frequencies of the generators is found, the mean frequency decline of the system is calculated according to the following formula:

$$\frac{df_c}{dt} = \frac{\sum_{i=1}^{n} H_i \frac{df_i}{dt}}{\sum_{i=1}^{n} H_i}, (Hz/sec)$$

Where,

$$\frac{df_c}{dt} = Rate\ of\ mean\ frequency\ decline\ of\ the\ system$$

$$\frac{df_i}{dt} = Rate\ of\ mean\ frequency\ decline\ of\ i^{th}\ generator$$

$$H_i = Inertia\ constant\ of\ the\ generator$$

Once the rate of mean frequency decline of the system is found, the size of the disturbance is calculated according to the following formula:

$$P_d = 2\frac{H_{sys}}{f_n}\frac{df_c}{dt}, (pu)$$

Where,

$H_{sys} = Equivalent\ inertia\ constant$

$f_n = Nominal\ frequency\ in\ Hz\ (50\ Hz)$

H_{sys} can be calculated with the following formulae:

$$H_{sys} = \frac{\sum_{i=1}^{n} S_i H_i}{\sum_{i=1}^{n} S_i}, (MVA)$$

Where,

$S_i = Rated\ apparent\ power\ of\ i^{th}\ generator$

After the size of the disturbance is found, threshold power, P_{th} , is determines. P_{th} is defined as the amount of overload at which the minimum curve of the frequency response of the weakest generator in the power system reaches the critical value of frequency. In this thesis, the critical value of frequency is taken as 95% of the nominal frequency, i.e. 47.5 Hz.

The value of P_d is compared with the P_{th} and the following cases can be derived:

If $P_d \leq P_{th}$, no load shedding is required

The disturbance is not dangerous for the power system, and the frequency decline can be recovered by the system spinning reserve. Thus, no load shedding is required in this case.

If $P_d > P_{th}$, load shedding is required

The disturbance is ranged as small disturbances, and under this condition the shedding is performed in two steps. The size of load to be shed is determined using this formula:

$$P_{sh} = 1.05(P_d - P_{th}), (pu)$$

The size and frequency setting of each step are determined as follows:

Step 1: The size of load shedding in this step is,

$$P_{sh1} = \frac{1}{3} P_{sh} , (pu)$$

$$P_{sh1} = Size\ of\ load\ shed\ in\ the\ first\ step$$

Step 2: The remaining load Psh2 to be shed which is tripped in this step is,

$$P_{sh2} = \frac{2}{3} P_{sh} , (pu)$$

The term $(P_d\text{-}P_{th})$ is multiplied by the correction factor 1.05

5.4 Algorithm

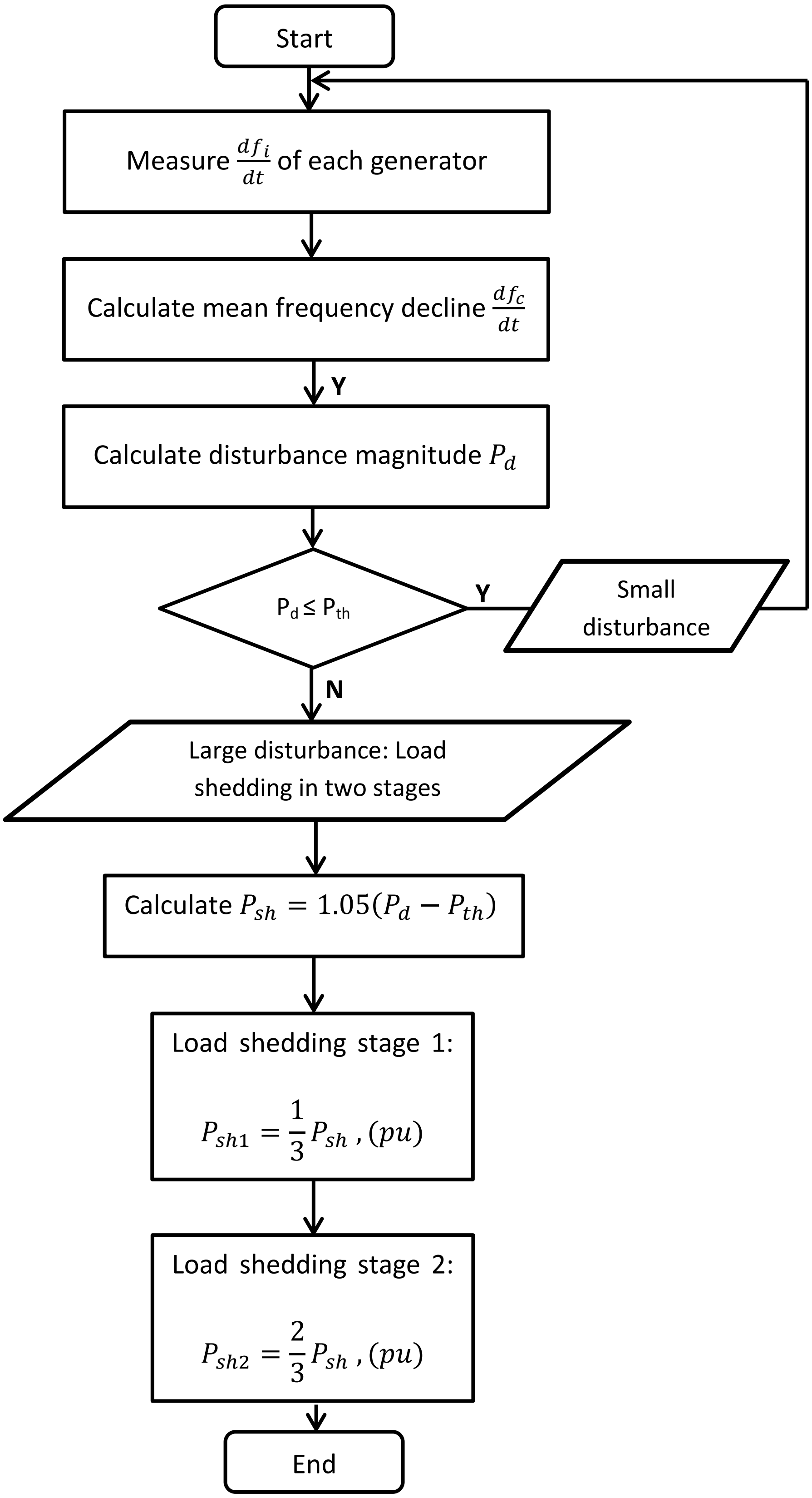


Figure 5.2: Algorithm Flow Chart

5.5 Load Prioritization

Prioritizing load blocks is an old concept, probably as old as the load shedding technique itself. According to a survey conducted by IEEE committee in 1968, about 86% of the participating utilities dropped low priority loads during their load shedding process. The same survey also showed that different departments were involved in determining the load priorities such as planning engineers (46%), sales (4%), management (12%), and other groups including operators (38%). Even a small group of utilities allowed rotating the customers for load shedding purposes. However, all of the priority and rotation schedules were predetermined, and the actual demand was assumed constant.

While the state-of-the-art load shedding algorithm allows the operators to choose the priority of loads on the fly via Human Machine Interface (HMI), an external program with higher level objectives − such as economic and social well-being should dictate the priorities by assigning a number to each load shedding block.

In the Intelligent Load Shedding Scheme, load blocks are shed in the order of their priority level and size, to equate or exceed the specified amount. To make sure that all low priority loads are disconnected before shedding high priority ones, they are separated and placed in different arrays. Each array, to which a priority number is associated, is organized from large load blocks to smaller ones; shedding larger loads first increases the speed and reduces the number of curtailed loads. Once a load block is shed, its values (load size, priority level and ID) will be moved to a different matrix, Curtailed Loads, which will keep track of shed loads as a reference for future restoration purposes.

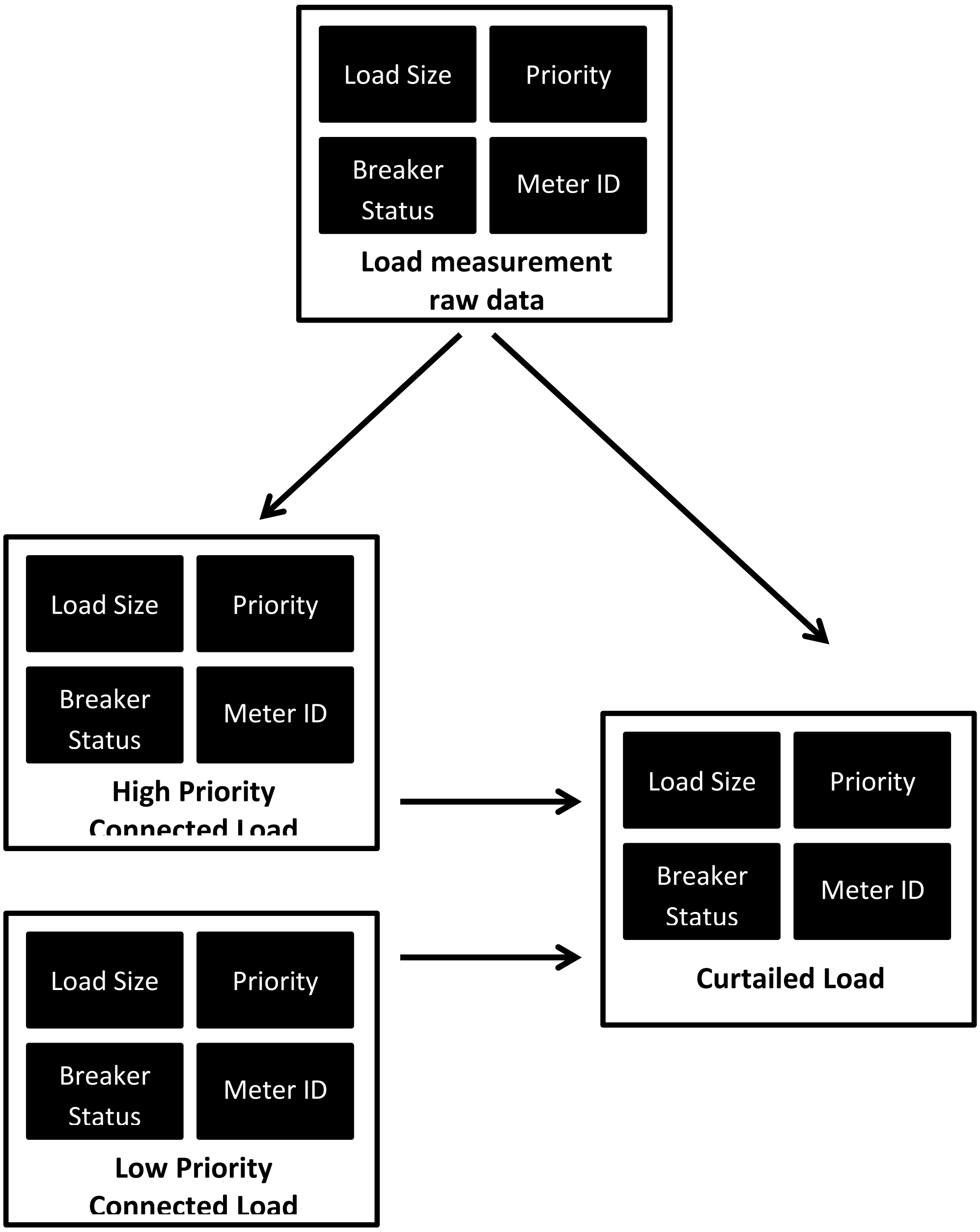


Figure 5.3: Load Prioritization

5.6 Process Delay

One of the most important factors in optimal load shedding is the time delay from the occurrence of the disturbance until the completion of the load shedding. Since the algorithm is very simple, even with a moderately fast computer system, Load Shedding Manager can complete the task very quickly. However, the command and data packets may suffer several types of delays while traveling through the network. The most common / important delays include:

1. Processing delay (negligible) is the results of testing the header of a packet and deciding where to send it. This is on the order of microseconds or less.
2. Queuing delay (τ_q) is the result of packets waiting to get transmitted onto the link; it depends on the number of packets that are already inside the queue. The queuing delay may take from zero to a few milliseconds.
3. Transmission delay (τ_t) is the time it takes to push all bits of a packet into the link. The transmission delay is practically on the order of the micro to milliseconds and is calculated dividing the length of a packet (L) by the transmission rate (R) of the link ($\tau_t = \frac{L}{R}$).
4. Propagation delay (τ_p), which depends on the length (d) and propagation speed (s) of the link ($\tau_p = \frac{d}{S}$). The propagation speed of Ethernet cables (coaxial cable, twisted pair and optical fiber) is close to speed of light.

The total communication delay is the sum of all the above delays. A number of studies have estimated the delay of WANs in a power system.

$$\tau_{total} = \tau_{processing} + \tau_q + \tau_t + \tau_p$$

Table 4.2 compares the WAN delays of different communication links in worst case scenarios.

Table 5.1: Delay in communication links

Communication Links	**Associate Delay (one way)**
Ethernet cables	≈ 100-150 ms
Digital microwave links	≈ 100-150 ms
Power line (PLC)	≈ 150-350 ms

Telephone lines	≈ 200-300 ms
Satellite link	≈ 500-700 ms

Communication delays in Wide Area Networks depend on many parameters such as the propagation and transmission speeds, the data packets size and length, and the type of the communications link which may even be unknown. In addition to that, there may be some delays associated with lost packets or jitters. Considering all these delays, a total delay of 200 ms can be assumed for a worst case scenario.

CHAPTER 6

CASE STUDY

6.1 Model

The standard IEEE 9-Bus System is used which consists of 9 Buses, 3 Generators and 3 loads. Islanding can be simulated by using the breaker if real generators are modelled. In Simulink, the generators are always ideal and hence frequencies of the generators never fall with the increase in load or outage of line or generator. In this case study, frequency data are used which is measured after a period of 0.08 sec, 0.16 sec and 0.24 sec. The rate of change of frequency is calculated my taking the mean of the rate of change of frequencies of these three intervals. Table 6.1 shows the generation and the load data for the test system.

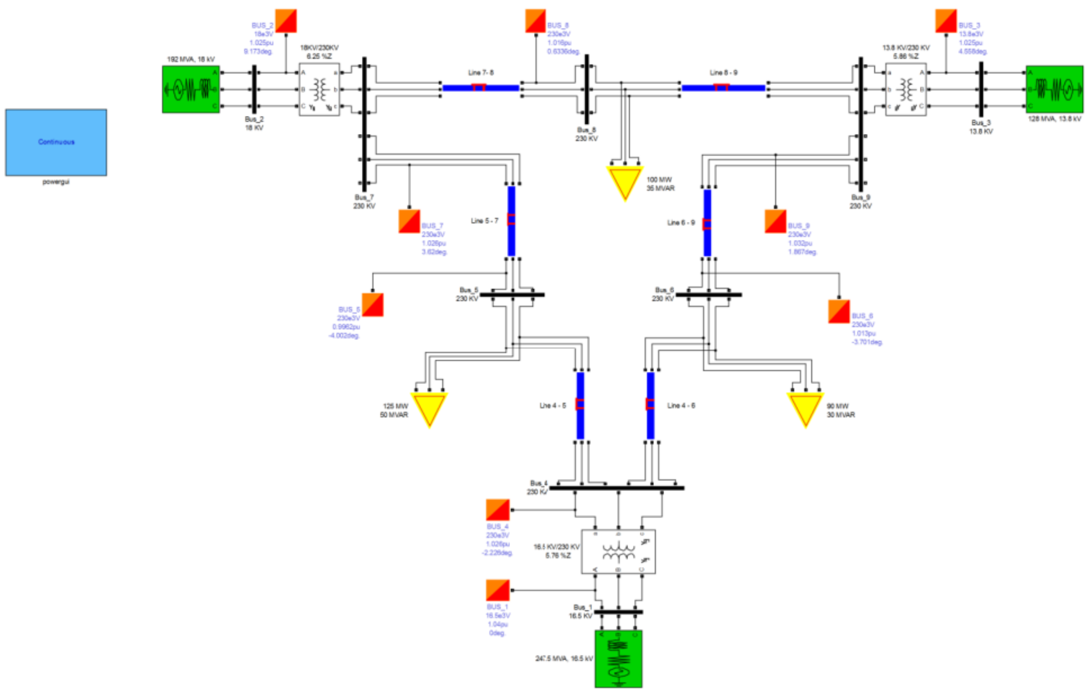


Figure 6.1: Test System (Standard IEEE 9-Bus Model)

Table 6.1: Generation and Load Data for the test system

Bus	S (MVA)	P_G (MW)	Q_G (MVAr)	P_L (MW)	Q_L (MVAr)
1	247.50	72.19	26.80	0	0
2	192.00	163.00	6.69	0	0
3	128.00	85.00	-10.78	0	0
4	0	0	0	0	0
5	0	0	0	125.00	50.00
6	0	0	0	90.00	30.00
7	0	0	0	0	0
8	0	0	0	100.00	35.00
9	0	0	0	0	0

Table 6.2: Generator Parameters

	Generator 1	Generator 2	Generator 3
Apparent Power (MVA)	247.5	192	128
Power Factor (PF)	0.9	0.85	0.85
Inertia Constant (H)	9.55	3.33	2.35

Table 6.3: Load Flow for the test system

From Bus	To Bus	P (MW)	Q (MVAr)
1	4	71.97	26.58
2	7	162.79	6.48
3	9	84.79	-10.99
4	1	-71.97	-23.45
4	5	41.12	31.92
4	6	30.85	9.12
5	4	-40.87	-29.74
5	7	-84.13	3.72
6	4	-30.68	-8.22
6	9	-59.32	4.80
7	2	-162.79	9.31
7	5	86.38	7.69
7	8	76.41	7.01
8	7	-75.93	-2.99
8	9	-24.07	-13.52
9	3	-84.79	15.07
9	6	60.64	0.99
9	8	24.15	14.26

6.2 Results and Discussion

The following sample frequencies are used for calculation of the mean rate of change of frequency of the system

Table 6.4: Frequencies of the generators in a time span of 0.24 sec

Time (sec)	Generator 1	Generator 2	Generator 3
0	50	50	50
0.08	48.74	48.17	47.7
0.16	47.25	46.95	46.3
0.24	45.9	45.58	45.25

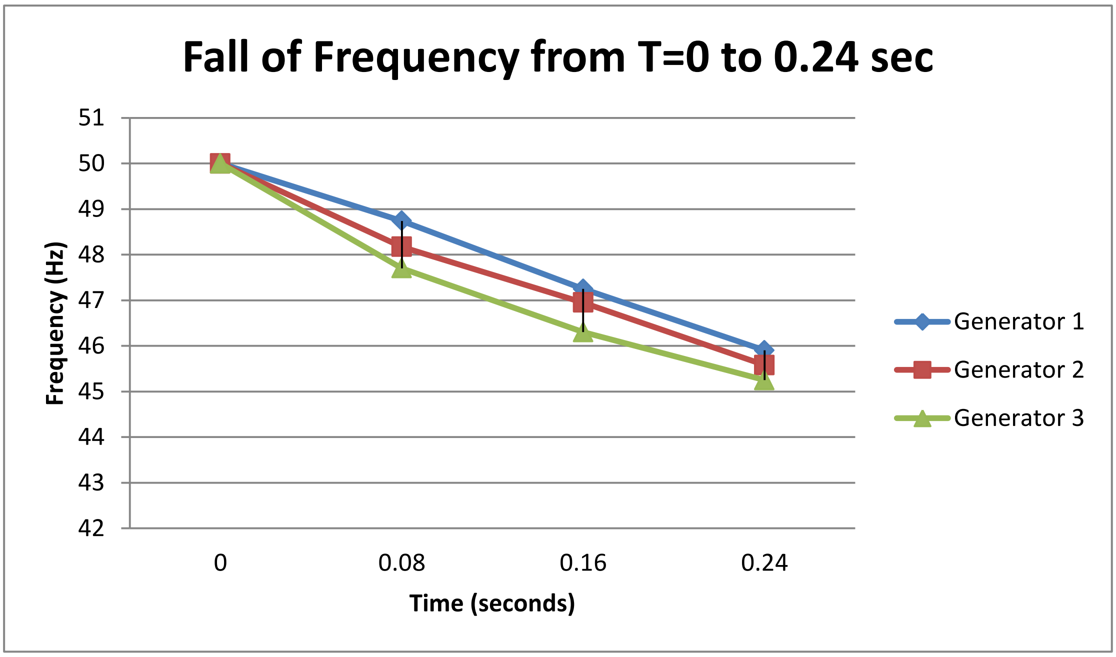
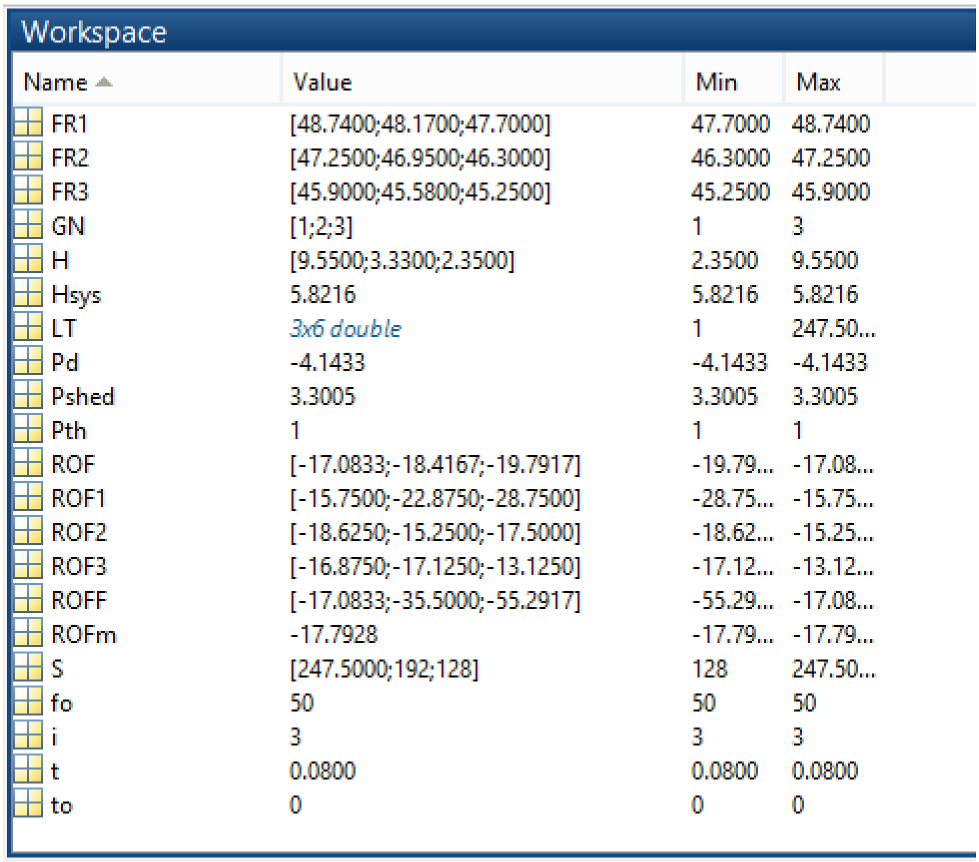


Figure 6.2: Fall of frequency from T=0 to 0.24 sec

A Matlab code is used to simulate the algorithm described in Chapter 5. Rate of change of frequency is calculated from the frequency data. P_{th} is taken as 1 pu.



Workspace

Name	Value	Min	Max
FR1	[48.7400;48.1700;47.7000]	47.7000	48.7400
FR2	[47.2500;46.9500;46.3000]	46.3000	47.2500
FR3	[45.9000;45.5800;45.2500]	45.2500	45.9000
GN	[1;2;3]	1	3
H	[9.5500;3.3300;2.3500]	2.3500	9.5500
Hsys	5.8216	5.8216	5.8216
LT	3x6 double	1	247.50...
Pd	-4.1433	-4.1433	-4.1433
Pshed	3.3005	3.3005	3.3005
Pth	1	1	1
ROF	[-17.0833;-18.4167;-19.7917]	-19.79...	-17.08...
ROF1	[-15.7500;-22.8750;-28.7500]	-28.75...	-15.75...
ROF2	[-18.6250;-15.2500;-17.5000]	-18.62...	-15.25...
ROF3	[-16.8750;-17.1250;-13.1250]	-17.12...	-13.12...
ROFF	[-17.0833;-35.5000;-55.2917]	-55.29...	-17.08...
ROFm	-17.7928	-17.79...	-17.79...
S	[247.5000;192;128]	128	247.50...
fo	50	50	50
i	3	3	3
t	0.0800	0.0800	0.0800
to	0	0	0

Image 6.3: Results Screenshot from Matlab Simulation

Table 6.5: Compete results from Matlab Simulation

Results	Generator 1	Generator 2	Generator 3
Inertia Constant (H)	9.55 MVA	3.33 MVA	2.35 MVA
Rated Apparent Power (S)	247.5 MVA	192 MVA	128 MVA
Frequency – 0.08 sec (Hz)	48.74	48.17	47.70
Frequency – 0.16 sec (Hz)	47.25	46.95	46.30
Frequency – 0.24 sec (Hz)	45.90	45.58	45.25
RoCoF – 0.08 (Hz/sec)	-15.75	-22.875	-28.75
RoCoF – 0.16 (Hz/sec)	-18.625	-15.25	-17.52
RoCoF – 0.24 (Hz/sec)	-16.875	-17.125	-13.125
RoCoF mean (Hz/sec)	-17.0833	-18.4167	-19.7917

The mean rate of frequency decline of the whole system, f_c = -17.792 Hz/sec

Inertia constant of the system, H_{sys} = 5.821

Size of disturbance, P_d = 4.143 pu

Hence, Load to be shed, P_{shed} = 3.30 pu

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

In order to remove the bottlenecks in the supply side of Micro Grids, this thesis presented a modified version of Under Frequency Load Shedding Scheme by incorporating communication techniques. This intelligent load shedding algorithm operates in a corrective mode to maintain the power flow in the main utility supply below their limits. In the case of islanding of the Micro Grid, the load shedding manager can help balance the electrical demand and generation of the Micro Grid. This thesis demonstrates the advantage of the algorithm in returning the system frequency back to 50 Hz after loss of generation.

Load shedding schemes are initiated in order to relieve system overload and correct the declining system frequency. This thesis is focussed on a load shedding scheme which not only corrects the system frequency but also improves the voltage profile throughout any system. The main purpose of this method is that it considers the rate of change of frequency and the voltage sensitivities before implementing the actual load shedding scheme. The scheme is simple and does not involve complicated calculations. It has proved to be successful in restoring the frequency within its pre-defined limits. It has also improved the voltage profile at certain buses which had critically low voltage before load shedding was applied.

In this type of load shedding, the amount of load to be shed is determined adaptively according to the size of the disturbance and hence avoids excess load to be shed. A strategy to shed an optimal number of loads in a distribution system, when it is islanded and does not have sufficient generation to supply all of the loads, is presented to stabilize frequency. Frequency, rate of change of frequency and generator parameters have been used to develop the load shedding strategy, which is implemented in relays responsible for shedding loads. The obtained simulation results are satisfactory.

7.2 Future Scope

There is a definite scope for improving the results by fine tuning the algorithm. Economic considerations need to be taken into account before shedding the load since certain loads cannot be kept offline. Also depending on the current market conditions the prices might vary. This needs to be kept in mind before initializing the load shedding scheme. Regular, hourly updates about the load are necessary to make an accurate and optimal load shedding scheme. Besides this a multiple contingency scenario considering the loss of a generator along with the loss of a transmission line would create a critical situation. The study and testing of the scheme in such a case is something which can be worked on in the future. With the advent of modern technology, synchrophasors have started carving a niche for themselves in the wide area monitoring and protection area. Briefly stated, a synchrophasor is defined as a phasor calculated from data samples using a standard time signal as the reference for the measurement. Synchronized phasors from remote sites have a defined common phase relationship. So far, synchrophasors have been used in determining Voltage stability indices, used in protective relays, for determining wide area angle stability and also used to check for black starting abilities of generators. One possible modification to the existing research would be collecting real time synchrophasor data and employing the proposed algorithm using this. Shown above were some of the possibilities which widen the scope for future research. Thus further analysis and developments are possible with the existing scheme which will enhance it to provide much more accurate and efficient results.

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APPENDICES

A) Rate of change of frequency, Size of disturbance and Load to be shed

```
B) % | Generator Number | f1 (Hz)| f2 (Hz) | f3 (Hz) | H | S |
C) LT=[1    48.74    47.25    45.9     9.55     247.5
D)      2    48.170   46.95    45.58    3.33     192.00
E)      3    47.7     46.3     45.25    2.35     128.00];
F)
G) fo=50;%initial frequency
H) to=0.0;%initial time
I) t=0.08;%checking time
J)
K) GN=LT(:,1);%Generator Number
L) FR1=LT(:,2);%Frequency of each generator at 0.08 second
M) FR2=LT(:,3);%Frequency of each generator at 0.16 second
N) FR3=LT(:,4);%Frequency of each generator at 0.24 second
O) H=LT(:,5);%Internia constants of the generators
P) S=LT(:,6);%Rated apparent power of generators
Q) Pth=100/100;%Treshold power (pu) with a base power of 100 MW
R)
S) ROF1=(FR1-fo)/(t-to);
T) ROF2=(FR2-FR1)/(t-to);
U) ROF3=(FR3-FR2)/(t-to);
V)
W) ROF=(ROF1+ROF2+ROF3)/3;
X)
Y) ROFm=(H(1)*ROF(1)+H(2)*ROF(2)+H(3)*ROF(3))/(H(1)+H(2)+H(3));
Z) Hsys=(H(1)*S(1)+H(2)*S(2)+H(3)*S(3))/(S(1)+S(2)+S(3));
AA)      Pd=2*Hsys*ROFm/fo;
BB)      ROFF=cumsum(ROF);
CC)
DD)      Pshed=1.05*((-Pd)-Pth);
EE)
FF)      disp('| GNo. | H | S | Freq.1 | Freq.2 | Freq.3 | RoCoF1
   | RoCoF2 | RoCoF3 | RoCoF | Cum.RoCoF |')
GG)      for i=1:3
HH)
   disp([GN(i),H(i),S(i),FR1(i),FR2(i),FR3(i),ROF1(i),ROF2(i),ROF3
   (i),ROF(i),ROFF(i)])
II)      end
JJ)      disp(sprintf('Rate of frequency decine of generator 1=
   %d',ROF(1)));
KK)      disp(sprintf('Rate of frequency decine of generator 2=
   %d',ROF(2)));
LL)      disp(sprintf('Rate of frequency decine of generator 3=
   %d',ROF(3)));
MM)      disp(sprintf('Mean rate of frequency decine= %d',ROFm));
NN)      disp(sprintf('Size of disturbance (pu)= %d',-Pd));
OO)
PP)      if -Pd<=Pth
```

```
        disp('No shedding needed');
    else
        disp('Loads need to be shed');
        disp(sprintf('Load to be shed (pu)= %d',Pshed));
    end
```