A PROPOSED LOAD SHEDDING SCHEME FOR EG LNG PLANT

By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
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CERTIFICATION OF APPROVAL

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Approved:

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Felipe Nguema Eman Andeme

ABSTRACT

Load shedding schemes are important and powerful tools nowadays for power systems. Load shedding is used as last resource to save islanded systems –under generation deficiency - from collapse. This report presents a prepossessed methodology for a design of automatic under-frequency load shedding scheme. The network of Equatorial Guinea Liquefied Natural Gas Plant has been chosen for implementation. The project involves one main objective which is to design and implement, through simulation, an automatic load shedding scheme suitable for the network. The plant load is divided into different categories. An under-frequency load shedding scheme base on rate of change of frequency, disturbance estimation and load categorization priority is designed to unable the plant to operate critical (mandatory) loads in the event of insufficient system generation. Project planning and implementation flow are also reported here.

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To my lovely parents, siblings, friends and colleagues, many thanks for your support

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LIST OF ABBREVIATIONS

LNG: Liquefied Natural Gas

UVLS: Under Voltage Load Shedding

UFLS: Under Frequency Load Shedding

EG: Equatorial Guinea

ROCOF: Rate Of Change Of Frequency.

SFR: System Frequency Response

Hz: Hertz

CHAPTER 1

INTRODUCTION

1.1 Background of study

Power system blackouts have been a historical problem in interconnected grids and even in isolated power plants. This is mainly due to the aim of obtaining power system efficiency and reliability leading power systems to operate close to their capacity limits. Yet, while intended to increase the utilization of system's generation and transmission assets tends to decreases system security and include the risk of complicated failure mechanisms. It is known that using excessive generation power more than required leads to a wasting of power that is traduced in terms of economy as losing money. For that reason, many generation companies run their generation units at nearest demanded load.

Because of the need to run power supply closer to demand special attention to maintenance is of the primary concern in electric utility companies.

High reliability supply is assured by high quality of installed elements, provision of reserve generation, use of large interconnected power systems capable of supplying each consumer via alternative routes and a high level of system security.

To maintain the reliability of electric power, it requires implementation of an appropriate protection scheme. Like that contingencies that cost money can be avoided. Protection scheme to use will depend on the referred power system parameters which can vary over time; otherwise, the variance may affect the stability of the power system.

1.2 Problem statement

Large power system disturbances sometimes cause the interconnected system to become separated into islands and the islands invariably have either an excess of generation or of load. Excess generation will often be controlled by fast action of the generating unit speed governors, as they respond to the rising frequency. Excess load, however, overloads the generating units, thereby causing the frequency to drop, sometimes to levels that may cause permanent damage to steam or gas turbines. To avoid this kind of damage, load shedding relays are often applied throughout the system to provide a means of helping balance the load to the remaining generation in the island

The frequency deviation caused by the imbalance between load and generation, is a very serious problem in the system that has an excess load. The frequency drop may cause a permanent damage to turbines, and plants themselves are subject to failure at low frequencies because their auxiliaries are unable to maintain normal output when the frequency is about 10 to 15% below normal. The primary method of restoring frequency is to shed load in appropriate amounts

Load shedding is an emergency control action designed to unsure system stability by curtailing system load to match generation supply. Load shedding protects excessive frequency or voltage decline by attempting to balance real and reactive power supply and demand in the system.

1.3 Objectives

This project involves the following objectives:

a. To review and understand load shedding practice and its importance.
b. To identify and distinguish load shedding approaches
c. To design an automatic load shedding scheme – which should includes load shedding steps, amount of load to be shed at each step, location of the shedable loads, placement of relay and relay settings - using EG LNG Plant as a model
d. To show the reliability of the design providing Matlab simulation results

1.4 Scope of study

This project has been done over duration of two academic semesters. The scope of study covers revision, understanding and analysis of different load shedding techniques; project planning that includes determination of project objectives, methodology and proposed design within timeframe of the mentioned two semesters. Different load have been grouped into different categories. A load shedding scheme base on priority has been designed to unable the plant to operate critical load in the event of detected system under stress.

The intention is to provide the plant with an appropriate managing blackouts plan. The scheme should be used whenever there is generation insufficiency. The design scheme is based on Adaptive under-frequency load shedding. The auteur found that Adaptive under-frequency scheme is the most efficient as it allows to shed the amount of load related to the disturbance.

The feasibility of this project is guaranteed from the fact that it has been properly planned and the equipments data required can be obtained. The area of the study is always subjected to frequent blackouts and that fact motivates plant managers to look for alternatives solutions to overcome the problem.

To unsure the feasibility of this project its flow was planned as provided in project methodology chapter. The Gantt charts for first semester and second semester can also be found in appendix B and appendix C respectively

CHAPTER 2

LITERATURE REVIEW

2.1 What is Load Shedding?

Load shedding is the process of deliberately removing (either manually or automatically) pre-selected customer demand from a power system in response to an abnormal condition to maintain the integrity of the system and minimize overall customer outages

When load and supply for an isolated portion of the power system are unequal, the generators in that area will speed up if there is a surplus of generation or slow down if there is a deficit. When the load in a power system significantly exceeds generation, the system can survive only if enough loads are separated from the system with a shortage in generation to cause generator output to be equal to or slightly above the connected load. The generation deficiency most often results from the loss of a major transmission line or transformer that is involved in a large transfer of power within the power system or between interconnected systems. Unplanned loss of a major generation source may also cause the deficiency. Frequency and or voltage are the reliable indicators that such a deficiency condition exists on the power system [1].

Figure 1 presents an equivalent circuit of a synchronous generator operating in parallel with a distribution network. In this Figure the synchronous generator SG feeds a load L.

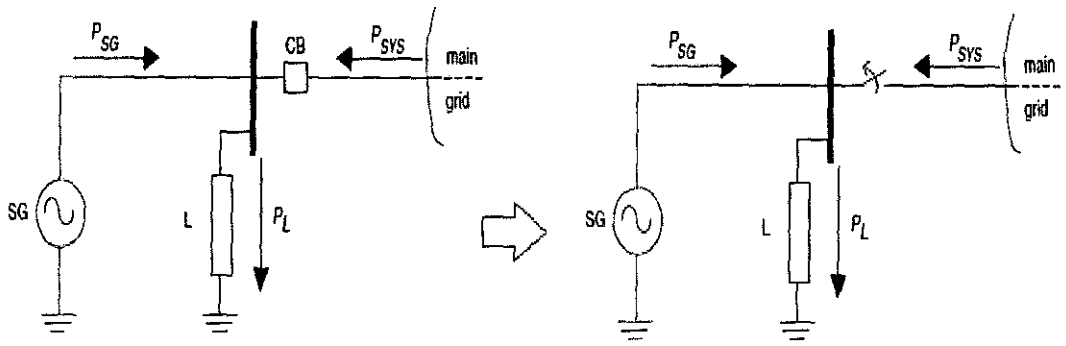


Figure 1 Simple network disconnected from the main grid

In figure 1 the difference between the electrical power P_{SG} supplied by the generator and the power P_L consumed by the load is provided by the main grid. Therefore the system frequency remains constant. If the circuit breaker CB opens, due to a fault for example, the system composed by the generator and the load becomes islanded. In this case there is an electrical power imbalance due to the loss of main power P_{SYS} [12]. This power imbalance will violate normal operating conditions in the islanded system; hence, the system will be unstable. If proper action is not taken on time, and depending on the magnitude of the disturbance, the islanded system may collapse leading to total blackout.

Power-load unbalance is the most dangerous condition for power system operation. Every unbalance between generation and load causes a deviation of the frequency from its steady state which - if not properly counteracted - can lead to system blackout; typical contingencies that may affect power system security are the loss of generators and/or of large interconnection lines [9].

2.1.1 Load Shedding Problem

Load shedding is performed in order to minimize the risk of a further uncontrolled system separation, loss of generation, or system shutdown. If sufficient load is shed to preserve interconnections and keep generators online, the system can be restored rapidly. If the system collapses, a prolonged outage will result [1]

When dealing with load shedding, several items must be taken into account. The most important of them are [11]: the definition of a minimum allowable frequency for secure system operation, the amount of load to be shed, the different frequency thresholds, the number and the size of steps [9]. All this considerations will further be discussed in the next sections of this chapter.

2.2 Types of load shedding

The literature discusses a wide variety of load shedding types. Basically load shedding can be classified from two perspectives. The first classification stresses on the control variable used to implement load shedding schemes. We have under-voltage load shedding scheme, under-frequency load shedding scheme or both under-voltage and under-frequency load shedding scheme according to if the control variable is the voltage, the frequency or both voltage and frequency respectively. For the purpose of this project, emphasis is given to under-frequency load shedding scheme. As presented in figure 2, there are two types of under-frequency load shedding approaches namely conventional load shedding and adaptive load shedding

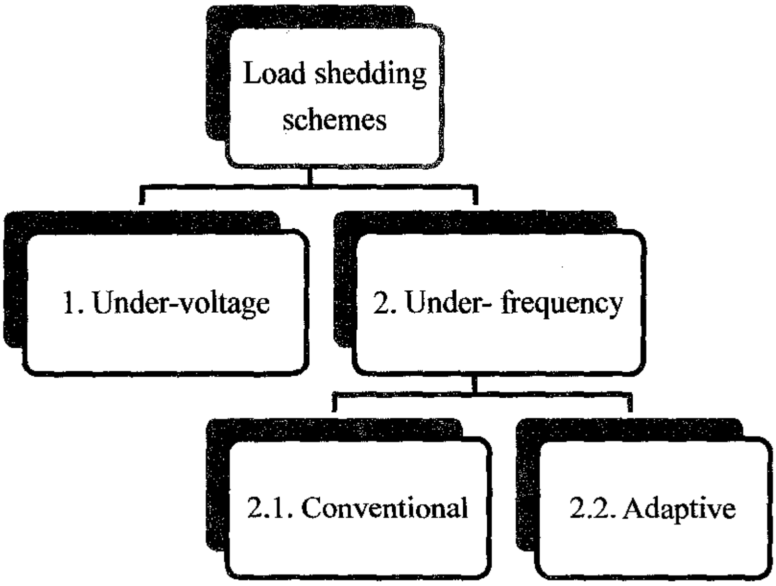


Figure 2 Organizational diagram providing types of load shedding based on the control variable used in the implementation.

The second classification is based on how the shedding is executed, and it can be either manual or automatic. For the purpose of this project emphasis is given to automatic load shedding; although a brief description of manual load shedding is provided. Automatic load shedding in turn can be centralized or distributed as shown in figure 3 below

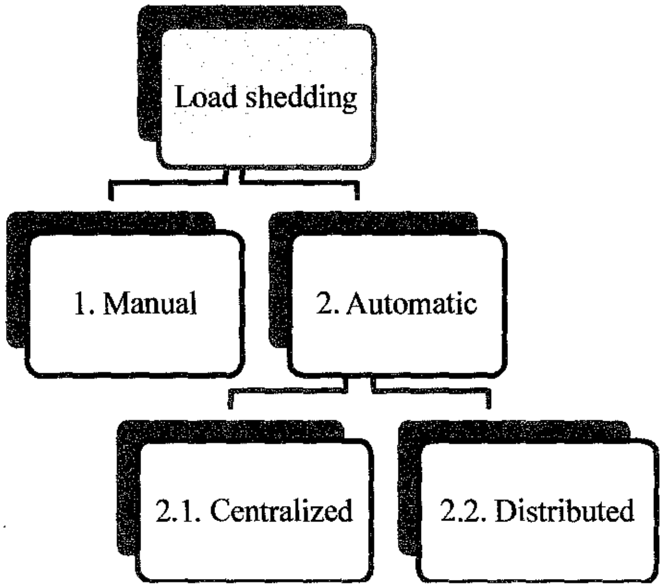


Figure 3 Organizational diagram showing types of load shedding based on its execution methods

2.3 Under-voltage load shedding

An under voltage load shedding scheme (UVLS) is generally applied as a safety net measure in situations where voltage collapse is anticipated and can potentially result in blackout conditions [4]. In recent years, load control, i.e., load shedding, has been adapted to be used to mitigate the possibility of a system collapse in the same way generators may be rescheduled [3], [5-8]

Either of two types of system disturbances generally triggers voltage instability: component outage and a sudden load increase in a power system. The occurrence of such disturbances usually increases reactive power demand of transmission network that should be provided efficiently, otherwise an outage of a heavily loaded transmission lines or tripping of a large generating unit may conduct the system toward collapse. Load shedding is usually initiated after exhausting all other counter-measures in attempting to arrest voltage instability [13].

Simply stated, the philosophy of UVLS is that when there is a system disturbance and the voltage drops to a pre-selected level for a pre-determined time, then selected loads are shed. The intention is that when load is shed for a disturbance, the voltage will recover to acceptable levels thereby avoiding a more widespread system voltage collapse. Developing a UVLS program requires coordination between protection engineers and system planners, who together can determine the amount of load and time delay required in the shedding program. System planning engineers conduct numerous studies using P-V (nose curves) as well as other analytical methods to determine the amount of load that needs to be shed to retain voltage stability under credible contingencies. Voltage collapse is most probable under heavy load conditions, so the amount of load to be shed depends on system peak load and generation sources. When considering the type of load to be shed, constant KVA loads such as motors are good candidates for shedding since they draw more current as voltage is decaying. [10]

Figure 4 shows an example P-V curve for a creditable contingency. The knee of the curve at which the voltage will collapse is identified as Vcollapse. A setting margin or safety factor is desired and then the accuracy band of the relay and VT is shown. The setting (Vsetting) must be set above these margins. As with all relay settings, dependability and security need to be balanced. If too small a margin is chosen, there is a risk of the scheme operating during allowable emergency conditions that do not yet require load shedding. If too small a margin is chosen, then load shedding could occur after the system passes below the nose curve voltage collapse point (Vcollapse) shown in the figure. [10]

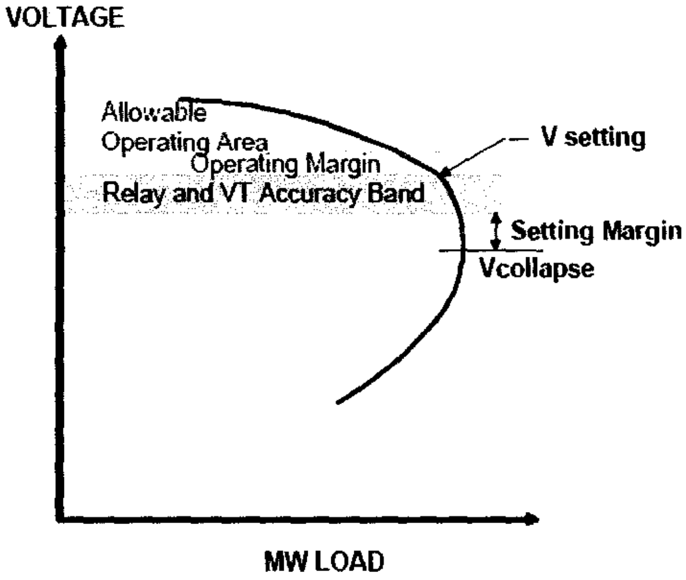


Figure 4 An example of P-V curve [10]

2.4 Under-frequency Load Shedding

In a power system, frequency is a measure of the balance of MW generation and MW load. When MW generation and MW load are exactly in balance, the frequency is at the normal level of 60 Hz. When load exceeds generation, the frequency goes down. The rate of decline depends on the inertia of the generators within the system. Under normal conditions, there are slight changes of frequency when load suddenly increases or generation trips off-line which results in a slight (hundreds of a hertz) reduction in frequency until the aggregate generation in the system can be increased to meet the new load condition. If there is a large negative unbalance between MW load and MW generation, the frequency is reduced. Under frequency load shedding (UFLS) schemes on the utility system are designed to restore the balance by shedding load [10]. Figure 5 presents the network of figure 1 with under-frequency relay – rate of change of frequency (ROCOF) – incorporated.

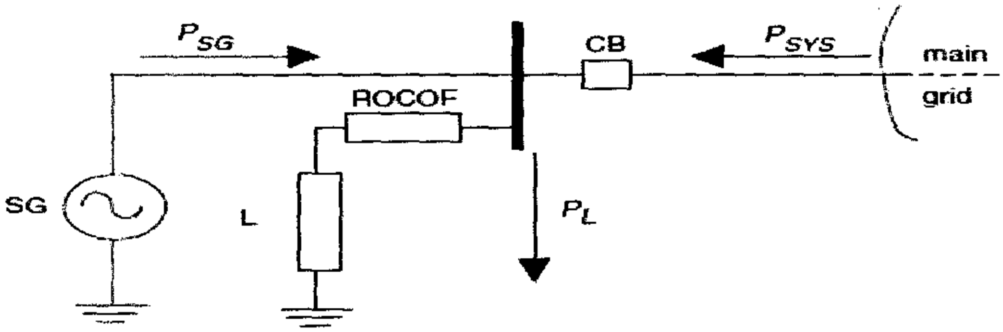


Figure 5 Simple network protected with under-frequency relay

2.4.1 Roots of frequency variation in power system

An electric power system behaves like a mechanical system in rotation. Figure 6 shows a simplified power system. Mechanical power is produced from water or steam and causes mechanical torque T_m on the shaft that joins the turbine to the generator. The generator transforms the mechanical power into electrical power. The load connected to the generator causes an electrical torque T_e on the shaft. As shown in Figure 6, a change in power demand or in production causes a fluctuation of the speed of the turbine-generator, resulting in fluctuation of the frequency of the power system.

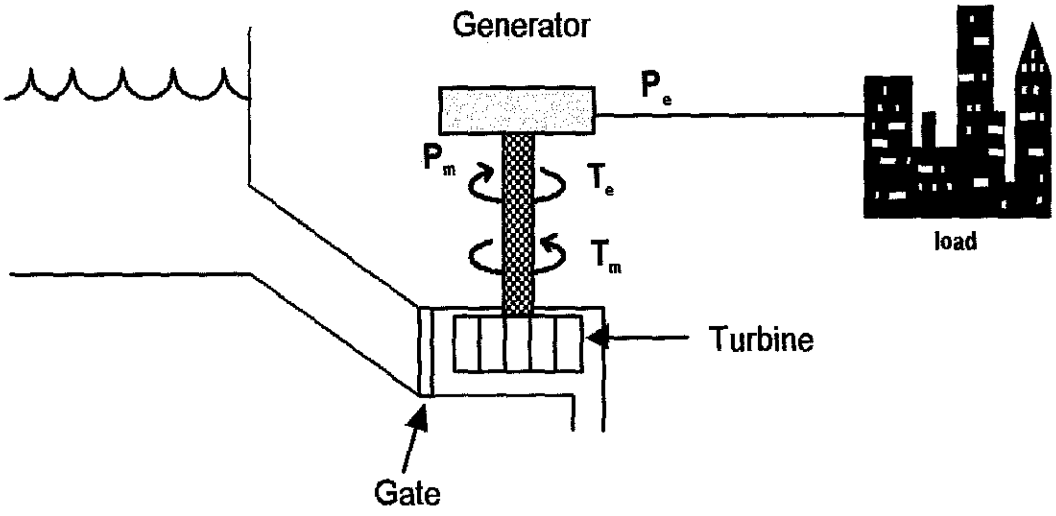


Figure 6 Power System Model [1]

The equation of motion represented by figure 6 is given by equation (1)

$$T_m - T_e = J\frac{d\omega}{dt} \tag{1}$$

Where

J is the total moment of inertia of the rotor mass in kgm^2
T_m is the mechanical torque supplied by the prime mover in N-m
T_e is the electrical torque output of the alternator in N-m
ω is the relative angular speed of the system in rad/s

The angular speed is related to frequency f as follows

$$\omega = 2\pi f \tag{2}$$

From equation (1) and following proper derivation as shown in appendix C, we come out with generator swing equation, i.e. equation 3, which shows how the frequency of a power system is affected by the power mismatch

$$P_m - P_e = P_a = \frac{2H}{\omega_s}\frac{d\omega}{dt} \tag{3}$$

Where

P_m	mechanical power in per unit
P_e	electrical power in per unit
P_a	accelerating power or power mismatch, ΔP in per unit
ω_s	synchronous speed or rated speed in rad/s
H	normalized inertia constant in seconds

$$H = \frac{stored\ kinetic\ energy\ at\ synchronous\ speed\ in\ mega-jules}{generator\ MVA\ rating} = \frac{\frac{1}{2}J\omega^2}{S_{rated}}$$

In equation (3) mechanical power, electrical power and acceleration power are all in per unit of total generation MVA base

2.4.2 Minimum frequency of operation

The minimum allowable frequency is imposed by the limitations of operation of system equipment. Specifically, the elements that are more sensitive to frequency drops are generators, auxiliary services and steam turbines [9], [15]. In the following and with reference to 60 Hz, the frequency values proposed by [9], [15] are quoted. The corresponding per cent values are given in parenthesis

Generators can operate at speeds much lower than steady state one, provided their MVA output is reduced. Power plant auxiliary services are more demanding than generators in terms of minimum allowable frequency: in fact, they begin to malfunction at a frequency of 57 Hz (95%), while the situation becomes critical at 53-55 Hz (about 88% - 92%). In that case, there is a cascade effect: the asynchronous motors of the auxiliary services are disconnected by their protections; anyway, the steam turbine is the equipment more sensitive to frequency drops. Turbine natural frequencies are kept – by design - far from the nominal speed, so that they are not likely to operate in a situation of resonance, which could destroy the turbine or cause a reduction of its life. It is safe to avoid that the frequency falls below 95%. In fact, every commercial turbine can sustain up to 10 contingencies at 57 Hz (95%) for one second without being jeopardized [9], [15]

2.5 Conventional Under-Frequency Load Shedding Scheme

System protection schemes are defined as protection strategies designed to detect a particular system condition that is known to cause unusual stress to the power system, and to take some kind of predetermined action to counteract the observed condition in a controlled manner [2], [17]. One of the most commonly used types of system protection schemes, generally accepted after the north-eastern blackout of 1965, is under-frequency load-shedding (UFLS) scheme [2], [18]

Conventional UFLS scheme is designed to maintain the balance of generation and consumption following power deficiencies which may be the consequence of generator or tie-line outages. Whenever frequency of the system falls below predetermined thresholds and it remains below the thresholds for a certain time, parts of the system load are shed in some predetermined steps [2].

Load-shedding relays are installed at constant locations of the system. These locations are usually substations which their loads have a lower degree of importance [2]. Common practice is to classified load as non-essential, essential, crucial, very crucial and mandatory in which non-essential loads are the first candidate to shed in the event of disturbance

Important steps of the conventional UFLS scheme design are as follows [2], [16]

2.5.1 Determination of anticipated overload

The anticipated overload determines the amount of protection that is to be provided. This value is obtained from equation (4) [2], [19].

$$L = \frac{P_L - P_G}{P_G} \tag{4}$$

Where,

L is the amount of anticipated overload in per unit (p.u),

P_G is the Total generation of the system and

P_L is the Total system Load

According to (4), the loss of 33 per cent of total generation results in 50 per cent overload and the loss of 50 percent of total generation results in 100 percent overload. Selection of L is arbitrary, however values greater than 50 per cent are not recommended due to possible over shedding during small disturbances [19], [20]

2.5.2 Determination of number of load shedding steps

All of the required load to be disconnected may be shed simultaneously, however this approach may lead to over shedding for small disturbances. A suitable alternative may be to divide the load to be dropped among several steps and shed a portion in each step. It seems that incorporating more steps results in more accurate load shedding, however this is not necessarily true and it must be verified by dynamic studies [23]. Furthermore, increasing the number of steps may cause problems in coordination between successive steps [22]. Typically 3 to 6 steps are recommended [19], [21].

2.5.3 Determination of the amount of load to be shed

The first step is to calculate the total amount of load to be shed to maintain frequency above minimum permissible frequency for the maximum anticipated overload. Total amount of load to be shed in a 60 Hz network is calculated using (2). [2], [7], [19]

$$LD = \frac{\frac{L}{1+L} - d\left(1 - \frac{f}{60}\right)}{1 - d\left(1 - \frac{f}{60}\right)} \tag{5}$$

Where,

LD	is total load that must be shed in per unit
L	is the per unit anticipated overload
f	is the minimum permissible frequency
d	is load reduction factor

For example, if the maximum coverage of UFLS is supposed to be 33%, L would be 0.5 per unit. Assuming $d = 1.7$ and $f = 57$ Hz for a 60 Hz system, the total amount of load to be shed becomes 0.268 of total system load. Afterward, the amount of load to be shed must be divided among the load shedding steps [2], [19]. Division of load among load shedding steps may be implemented in various ways. If a great amount of load were dropped in the first step, the scheme would be suitable for large mismatches between generation and load. However, it may result in over shedding for small disturbances. Conversely, if a small amount of load is dropped in the first step and a large amount is dropped in the last step, the scheme will be more suitable for small disturbances. However, it may result in large frequency decline for large disturbances. A suitable alternative may be to shed small amount of load in the first step, large amounts in intermediate steps and a small amount in the last step [19], [24]

2.5.4 Calculating relay settings

The last step is to determine relay settings. After determining the amount of load to be shed in each step, the frequency at which load is dropped for step number one is calculated using relay characteristics curves. Then, setting of the next step is determined using (3).

$$\text{Setting} = \text{previous clearing frequency} - \text{safety margin} \qquad (6)$$

Safety margin is involved to compensate for the inaccuracies of relays, breakers and other uncertainties.

2.6 Adaptive under-frequency load shedding scheme

Conventional methods of system load shedding are too slow and do not effectively calculate the correct amount of load to be shed. The reason lay on the fact that loads are not constant because the system loading may shift and the load may vary, thus making it difficult to predict how much load will be shed at a specific time and location. The results are either excessive or insufficient load reduction [26]. In addition, the conventional linear frequency type of relaying, which possesses multiple frequency settings operating on the shed-and-see principle, could also lead to either over or under load shedding. The latter implies a lower setting frequency than nominal while the former leads to frequency overshooting, sometimes to unacceptable harmful levels to the turbine blades. This method proved to be inadequate to avoid blackouts, and was therefore improved by new relaying methods [25].

Alternative to conventional method is the adaptive approach that can adjust the amount of load shed based on the initial rate of system frequency decay It is assumed that each relay incorporates a microcontroller and may receive data from a control centre It is then possible to adjust the load-shedding relay operating criteria as system conditions change [25], [26]. With this approach, the scheme is online tuned to the estimated magnitude of the disturbance

2.6.1 Design Considerations of an Adaptive Load Shedding Scheme

For the design of an adaptive load shedding scheme the following three problems much be considered [21], [25], [27]:

1. Estimation of the magnitude of the disturbance
2. Location of disconnection
3. Control action taken by individual relays

The first problem is solved using the generator swing equation, (3). Previously written equation (3) when it is applied to a system of N generators it takes the following form

$$P_{m\_sys} - P_{e\_sys} = P_{a\_sys} = \frac{2H_{sys}}{\omega_s}\frac{d\omega_{sys}}{dt} \tag{7}$$

Or, alternatively substituting (2) into (7), results

$$P_{m\_sys} - P_{e\_sys} = P_{a\_sys} = \frac{2H_{sys}}{f_s}\frac{df_{sys}}{dt} \tag{7}$$

Where

$f_s = f_n$, is the nominal frequency of the system

$$H_{sys} = \sum_{i=1}^{N} H_i = \sum_{i=1}^{N} H_{machine}\left(\frac{S_{Bmachine}}{S_{Bsys}}\right) \tag{8}$$

$$f_{sys} = \frac{\sum_{i=1}^{N}(H_i f_i)}{\sum_{i=1}^{N} H_i} \tag{9}$$

$$P_{m\_sys} = \sum_{i=1}^{N} P_{mi} \tag{10}$$

$$P_{e\_sys} = \sum_{i=1}^{N} P_{ei} \tag{11}$$

All H_{sys}, P_{mi} and P_{ei} are based on system base VA, S_{Bsys}

In a power system when a given amount of load is to be shed, based on system constraints, the first step is to determine the load(s) that should be shed. The factors that are generally considered in the process of determination of load(s) to shed is power rating of a load and/or some predetermined priority based on importance of a load. From the system benefits point of view, other system critical natures of loads should also be considered while determining whether to shed a load. These system critical natures of loads may include inrush current, harmonic content, restoration process, power factor and full load power rating [28].

Loads with higher active power rating tend to be shed first so that least number of loads is curtailed to satisfy system constraints. With total power rating of loads curtailed being the same, less number of loads shed indicates less cost [28]

In most utilities, importance levels of loads are categorized as Vital, Semivital, and Nonvital. The definitions are as follows [28]:

Nonvital - Readily sheddable loads that can be immediately secured without adversely affecting plant operations, survivability, or life.

Semivital - Loads important to the plant but that can be shut down in order to prevent total loss of plant's electrical power.

Vital (Essential) – Non-sheddable loads that affect the survivability of plant or life. Power to these loads is not intentionally interrupted as part of a load shedding scheme.

The proposed scheme reported here uses the classification of the EG LNG (Equatorial Guinea Liquefied Natural Gas) Plant which gradually categorizes load as non-essential, essential, crucial, very crucial and mandatory. Non-essential loads are the first candidate to shed in the event of system disturbance due to excess of system load. Mandatory loads however, cannot be shed intentionally due to their critical role in the operation of the plant.

The set of criteria used for load prioritization are not unique and it changes from utility to utility.

The control action manages the downstream relays depending on the area and it is used to accomplish the fast operation of the load shedding defense plan required, namely for frequency stability in case of network islanding. The proposed load shedding scheme with a centralized computerized power management system will provide fast and optimal load management by utilizing system topology, gas turbine generators power generation; load demand and actual operating conditions. The relays should read the slop of frequency decline, also known as rate of change of frequency (ROCOF) all the time. A critical frequency decline speed should be provided and used as a set point of the control loop. Then, whenever ROCOF is below the set point, estimate the disturbance and provide an adequate load shedding.

In this proposed load shedding scheme for EG LNG plant the author chose to use an adaptive approach. Adaptive under-frequency load shedding scheme and the rate of change of frequency will be emphasized in next sections.

2.7 Frequency analysis

The frequency performance of an islanded power system can be represented approximately by a linear system frequency response (SFR) model shown in figure 10 [21]. All the parameters of the model are in per unit on a MVA base equal to the total rating of all generating units in the island.

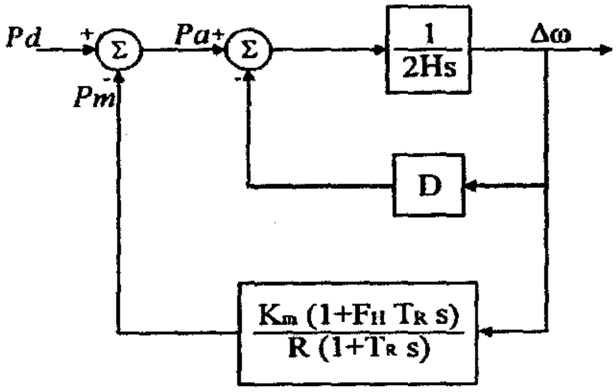


Figure 7 The SFR Model with Disturbance Power as Input [21]

The model behavior depends on five factors:

a) The gain, $\mathbf{K_m}$

b) The damping factor, **D**

c) The inertia constant, **H**

d) The reheat time constant, $\mathbf{T_R}$ and

e) The high pressure power factor of the reheat turbines, $\mathbf{F_H}$

For this system model we compute the frequency response in per unit to be

$$\Delta\omega = \left(\frac{RP_d}{DR + K_m}\right)\left[\frac{(1 + T_R s)\omega_n{}^2}{s^2 + 2\zeta\omega_n s + \omega_n{}^2}\right] \tag{12}$$

Where

The square-root of natural frequency, ω_n is given by (13)

$$\omega_n{}^2 = \frac{DR + K_m}{2HRT_R} \tag{13}$$

And

The damping ratio, ζ is set to be

$$\zeta = \left[\frac{2HR + (DR + K_m F_H)T_R}{2(DR + K_m)}\right]\omega_n \tag{14}$$

The above equation (12) indicates that the per unit speed or frequency can be computed for any disturbance P_d. For sudden disturbances, large or small we are interested in P_d in the form of step function P_{Step}, which changes to the following form

$$\Delta\omega = \left(\frac{RP_{step}}{DR + K_m}\right)\left[\frac{(1 + T_R s)\omega_n{}^2}{s(s^2 + 2\zeta\omega_n s + \omega_n{}^2)}\right] \tag{15}$$

Equation (15) can be solved directly to write the per unit frequency deviation in the time domain as follows:

$$\Delta\omega(t) = \left(\frac{RP_{step}}{DR + K_m}\right)\left[1 + \kappa e^{-\zeta\omega_n t} sin(\omega_r t + \varphi)\right]u(t) \quad p.u \tag{16}$$

Where

$$\kappa = \sqrt{\frac{3\zeta^2 + \omega_n T_R(\omega_n T_R - 4\zeta) + 1}{1 - \zeta^2}} \tag{17}$$

$$\omega_r = \omega_n\sqrt{1 - \zeta^2} \tag{18}$$

And

$$\varphi = tan^{-1}\left(\frac{\sqrt{1 - \zeta^2}}{2\zeta - \omega_n T_R}\right) \tag{19}$$

2.8 Manual load shedding

Power system operating guidelines generally permit individual operating utilities to shed load manually, or open ties with adjacent utilities at a frequency below which all automatic under-frequency or under-voltage load shedding schemes have operated. This manual intervention may be required to prevent further frequency/voltage decline, or to recover and restore system frequency/voltage back to the nominal value

Manual or operator/SCADA (supervisory control and data acquisition system) initiated load shedding generally cannot be accomplished fast enough to prevent partial or complete system collapse. Automatic schemes, employing frequency or voltage sensing relays, are therefore employed to shed individual loads or blocks of load at discrete under-frequency/ under voltage set points or at specific frequency rates of decline. These set points are predetermined based on guidelines created by power pools covering a wide geographic area [2].

Manual load shedding may be accomplished at the substation or from a central control via a SCADA system.

2.9 Automatic load shedding

More recently, microprocessor-based circuit reclose controls have been developed that include frequency/voltage sensing elements. This development presents the possibility of performing distributed partial feeder load shedding, or even individual customer load shedding [2].

Power system substations are often the focus of automatic load shedding schemes because they present access to tripping devices (line and feeder breakers) that supply blocks of load, and they include the necessary infrastructure to support frequency/voltage sensing relays. Two popular schemes to accomplish automatic load shedding are centralized automatic load shedding and distributed automatic load shedding.

2.9.1 Centralized automatic load shedding

Centralized load shedding is defined as the use of frequency/voltage measurement at one point in the substation, combined with control logic, to initiate the shedding and possible restoration of load feeders in a substation. It differs from distributed load shedding in that only one frequency relay is applied to perform the frequency measurement to initiate load shedding to the substation feeders

2.9.2 Distributed automatic load shedding

It is an individual feeder-based load shedding method. Historically, load shedding schemes have been applied at the bus level. With the proliferation of numeric, multifunction feeder protection relays that include under-frequency tripping as an optional setting, it has become more economical to apply under-frequency load shedding at the circuit level. Reliability increases, as the user is no longer depending on a single relay to sense the under frequency/under-voltage condition at a station. Also, defeating under-frequency tripping for an under-voltage condition, and the capability to drive multiple under-frequency protection elements from different voltage sources, greatly enhances security. Numeric circuit protection senses an under-frequency condition, and after a preset time delay, operates an interrupting device such as a recloser or breaker, thus de-energizing only the desired circuit load. This allows utility planners to be more precise with their selection of loads to be shed. Since most numeric protection relays also have logic for reclosing if certain parameters are met, this logic can be customized to fit the post load shed restoration practice

2.10 Load restoration

When restoring load after a load shedding event, the primary concern must be maintaining system reliability. Load should be added no faster than generation is added. Adequate reactive power sources must be available to control system voltage.

In many regions, manual load restoration is preferred. This places the burden of balancing load and generation and voltage regulation on the system operator. However, today's technology allows for gathering the appropriate information for intelligent restoration where information is brought to the operators as recommendations.

2.10.1 Important considerations on load restoration

Rapid and excessive load restoration can cause a repeat of the instability condition that caused the original load shedding operation. However, instability condition can occur if too much load has been shed. Automatic load restoration may be necessary to arrest the over-frequency or excess of voltage condition in a timely fashion. As with load shedding, sufficient studies should be performed to determine where and how load would be restored.

When systems have islanded from neighboring systems, automatic load restoration may be inhibited until the system interties are restored. It may be preferable to let governor action on frequency-biased generator controls operate first to bring the system frequency back into normal operating range. However, generators are often set to trip on over-speed, so it may be preferable to perform automatic over-frequency load restoration before the frequency gets to that point where generation is tripped automatically [2].

The load shedding and load restoration schemes must be designed to work in concert with the protection and control schemes that trip and close the line or feeder breakers. The load restoration scheme must reset any lockouts operated by the load shedding scheme, or otherwise create a permissive condition to allow manual/SCADA-controlled breaker closing. This can be supervised by a SCADA contact to allow central supervision of restoration [2].

As with load shedding, microprocessor-based relays used with a communication system can allow supervisory load restoration schemes to be modified to adjust for variations in system conditions. With the long time delays between load restoration steps, this function can be controlled manually by the system operators or it can be controlled by an automatic SCADA routine

CHAPTER 3

METHOLOGY

3.1 Procedure identification

Figure 7 below reflects the methodology and flow chart that is been used to implement this project:

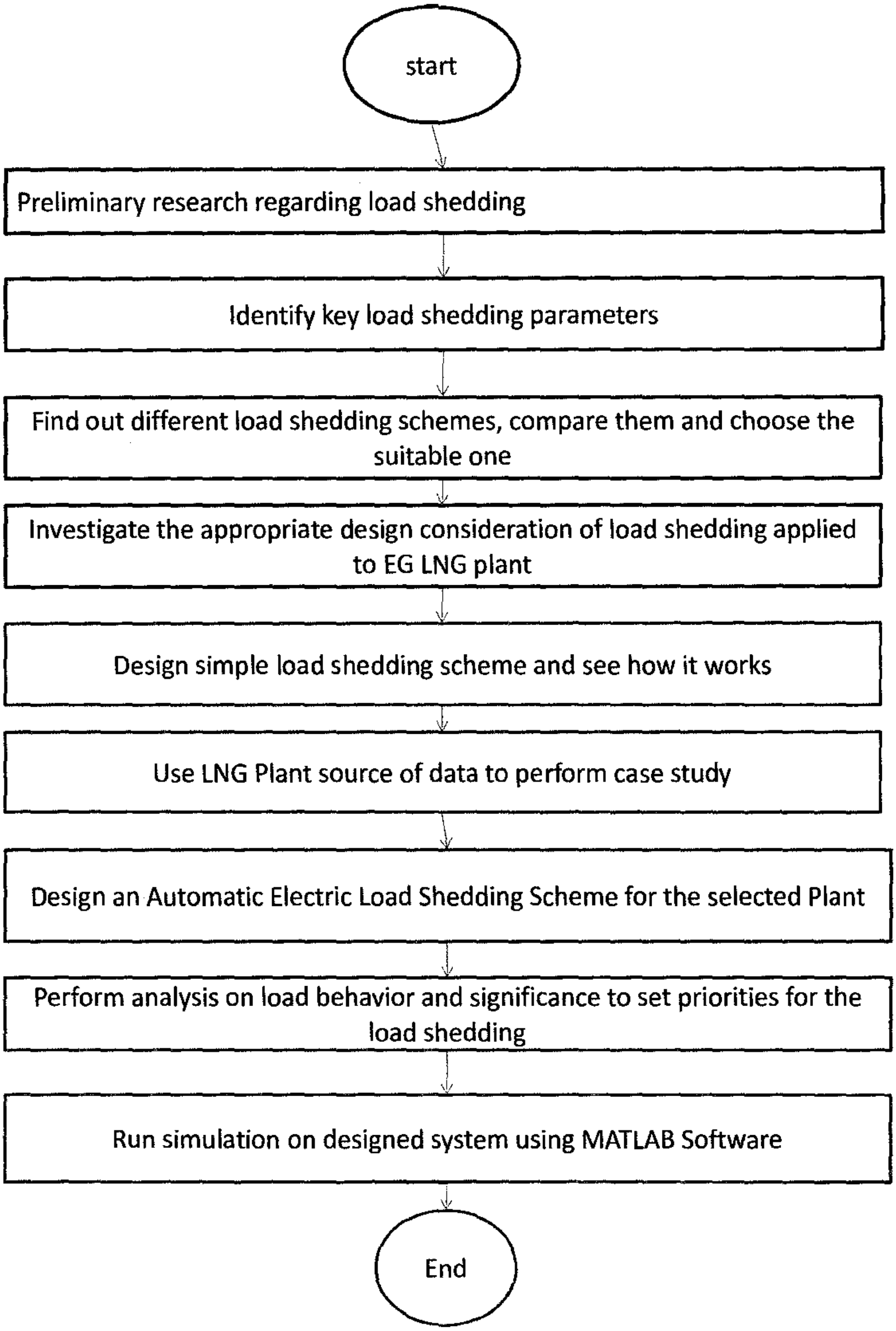


Figure 8 Flow chart of two semester project plan

The methodology here refers to the planning and scheduling of the project. The flow chart of figure 8 captures the basics steps taken through the project.

The project Gantt charts can be found in appendices and they are the summary of the project scheduling and progress.

3.2 Tools

To carry out this project the author has used different tools mainly software as the project is a design and simulation project. Amount used software we have

3.2.1 Matlab

Matlab® is a high-performance language for technical computing. it integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. this collection includes but is not limited to the following topics

Graphics. How to plot data, annotate graphs, and work with images.

Programming. How to use Matlab to create scripts and functions, how to and manipulate data structures

Beside Matlab, Microsoft office Visio 2007 was also used for drawings.

Microsoft word has been vital in writing the reports whereas Microsoft power point has always been used for project presentations.

CHAPTER 4

RESULTS

4.1 Company background

Equatorial Guinea LNG or EG LNG is a natural gas producer company in the Gulf of Guinea, West Africa. EG LNG Train 1 Plant is situated in the area named Punta Europa in Malabo, the capital city of Equatorial Guinea. Punta Europa Industrial Complex comprises so far a total of three gas producer companies. EG LNG operates Liquefied Natural Gas (LNG) Train 1 Plant. Marathon Equatorial Guinea Production Limited is the operator of Alba Plant producing Liquefied Petroleum Gas (LPG). The third gas company present in Punta Europa industrial complex is Atlantic Methanol Production Company (AMPCO). This project is about load shedding in EG LNG Train 1 Plant.

4.2 Electrical System Description

Power for LNG Plant is provided through power arrangement with Alba Plant (Phase 2) utilizing four (4) GE frame 5PA gas turbine generators. Two GTG's, each site rated 22.210 MW are located in the Alba Plant and two GTG's, each site rated 22.210 MW are located in the LNG Train 1Plant. To satisfy N+1 reliability criteria during normal operation three (3) out of four (4) turbine generators supply total load for both Alba Plant and Train 1 Plant and one generator is kept as spinning reserve.

The Standby Generator (1DG-3105) site rated 2600 kW is sized to carry the essential load for train one and start one of the turbine generators at LNG Train 1 or one of the turbine generators' starting motors at Alba Plant. A simplified one line diagram of Punta Europa power sharing is shown in figure 8,

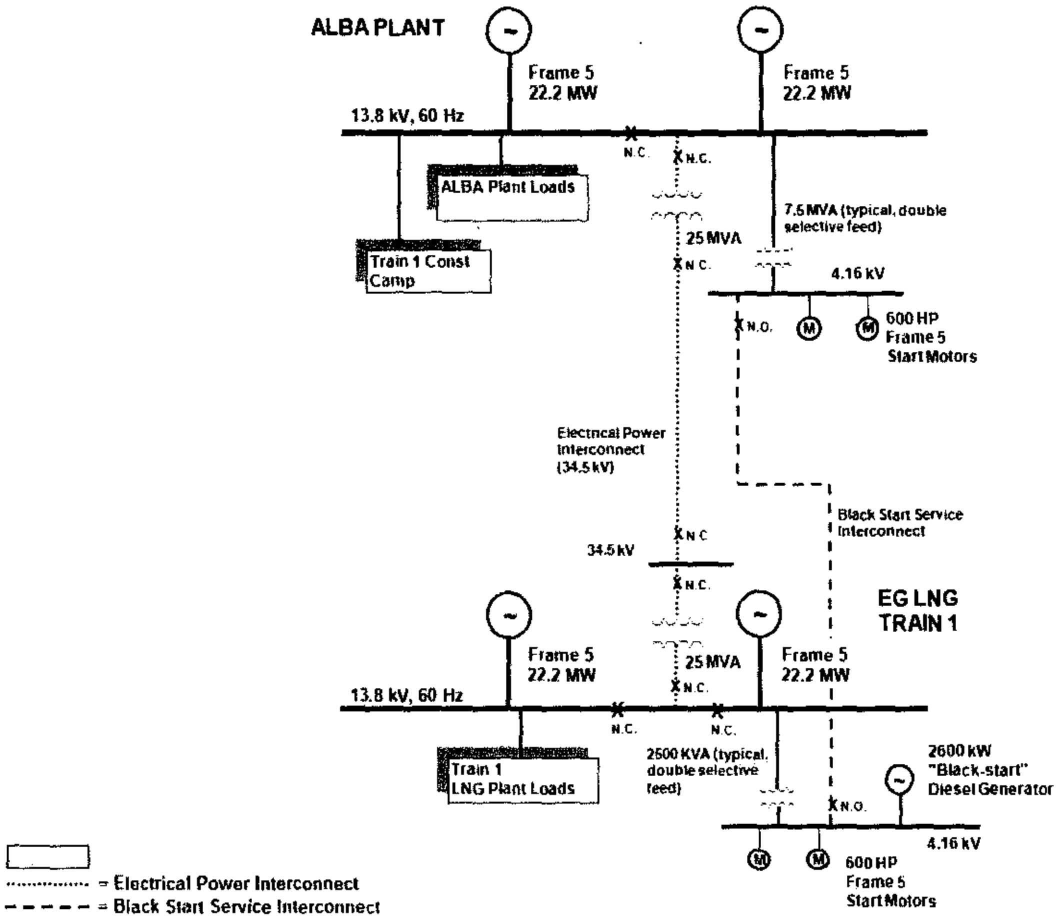


Figure 9 Electrical Power Interconnect and Black Start Services One-Line Diagram

4.3 System load

Train 1 power system total operating load with no diversity factor is 23077 kW at 87.8% PF with six LNG Loading pumps running. The loading pumps operating load is 2330 kW. The total system operating load of Train 1 without the LNG loading pumps running is 20747 kW at 87.8% PF. The total connected load of Alba Plant is 23334 kW. The total system load of Punta Europa with six LNG pumps running is 46411 kW. Table 1 summarizes Punta Europa system load.

Table 1 Summary of system load of Punta Europa

CASE 1: With LNG Pumps	CASE 1: Without LNG Pumps	
23077 kW	20747 kW	**Train 1 Plant**
23334 kW	23334 kW	**Alba Plant**
46411 kW	44081 kW	**Total at Punta Europa**

4.4 System generation

Each of the four turbine generators (GT) at Punta Europa is site rated 22210 kW. When all four TG are running at full load we have a 4 x 22210 kW, yielding 88840 kW. When the system operates with three (3) running and one generator on off-line reserve, the total capacity of three generators is 3 x 22210 kW, resulting in 66630 kW. When the system operates with two generators running and two off-line, the total capacity is 2 x 22210 kW, which in turn yield 44420 kW. In the last two cases, if there is an unexpected failure of one of the turbine generators in operation, the generation capacity will be less than the demanded load.

For the purpose of this project, it is assumed that only three (3) turbine generators are operating in parallel and the fourth generator is maintained offline. Table 2 presents the alternatives generation capacities considered in this project

Table 2 Different alternatives of capacity at Punta Europa

CASE NUMBER	NUMBER OF GENERATORS RUNNING	TOTAL CAPACITY	
		kW	kVA
1	3	66630	78390
2	2	44420	52260
3	1	22210	26130

Assuming the plant is running with peak load – 46411 kW - and one of the three turbine generators trips; from table 1 and 2 it can be seen that generation capacity will be less than needed to satisfy the demand. Then, Load shedding will be required.

The load shedding design is applied only to EG LNG Train 1 site considering Alba Plant load as one block of mandatory load.

4.5 Design consideration

4.5.1 Cases of power mismatch in per unit

To design a load shedding scheme for EG LNG Plant the author has considered two cases of power mismatches.

In the first case we compare total demanded load with total generation of 44420 kW. And in the second case the total demanded load is compared with 22210 kW generation. The per unit values of table 3 are obtained by dividing active generation power (kW) or active load power with the respective apparent power (kVA) of each case

Table 3 Comparison of generation and load for different generation cases

Per unit generation (P_G)	**Per unit load (P_L)**	**Power mismatch (P_G-P_L)**	
0.85	0.888	**-0.038**	**CASE 1** (52260 kVA base)
	1.769	**-0.919**	**CASE 2** (26130 kVA base)

4.5.2 Load classification

The total load of the plant has been classified based on its importance for plant operation. There are five categories of load: non-essential, essential, crucial, very-crucial and mandatory. Plant load classification and categorization can be found in appendices A and B. Additionally, figure 9 presents on side load classification and categorization of EG LNG plant.

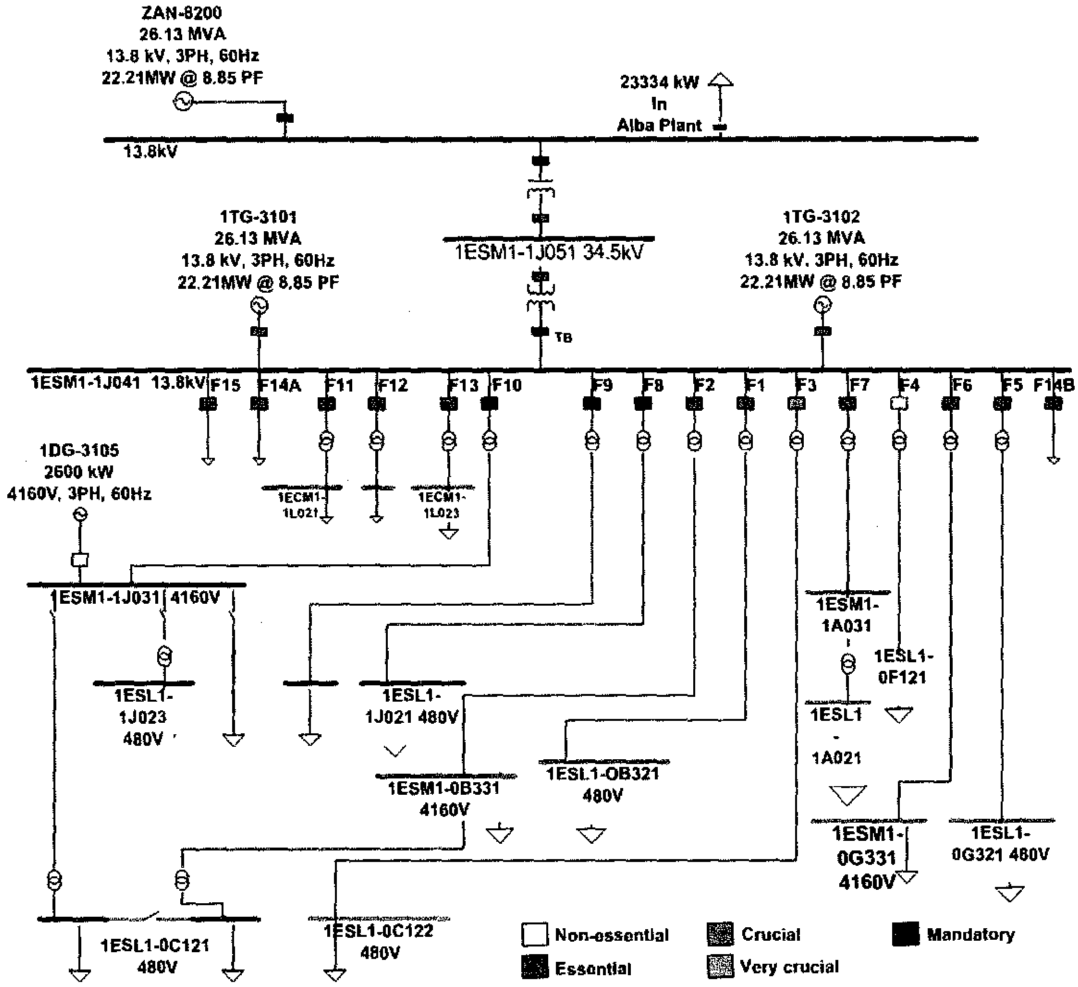


Figure 10 Simplify one line diagram with load priorities

4.5.3 *Load under relieve*

The available amount of load to be shed is known as load under relieve. Taking into account the priorities of load mentioned earlier, then the under relieve load of the plant can be summarized as indicated in table 4 which is the summary of appendices A and B

Table 4 Load under Relieve

LOAD UNDER RELIEVE			
Category	**Per Cent of total 46411 kW**	**CASE 2**	**CASE 3**
		Per Unit of 52260 kVA	**Per Unit of 26230 kVA**
Non-Essential	0.46	0.004	0.008
Essential	32.38	0.287	0.578
Crucial	6.49	0.057	0.116
Very Crucial	1.95	0.017	0.035
TOTAL	**41.28**	**0.365**	**0.737**

4.6 Design of Load Shedding Scheme

4.6.1 Frequency Analysis Results

The time response of equation (16) is a damped sinusoidal wave form, as shown in figure 11, where equation (16) has been converted to give the actual frequency in hertz.

The average system parameters for this design are as follows:

a) The gain, $\mathbf{K_m} = 0.85$;
b) The damping factor, $\mathbf{D} = 1.0$;
c) The inertia constant, $\mathbf{H} = 3.5$ seconds
d) The reheat time constant, $\mathbf{T_R} = 8.0$ seconds; and
e) The high pressure power factor of the reheat turbines, $\mathbf{F_H} = 0.3$

All parameters are estimated based on common knowledge of typical system designs []

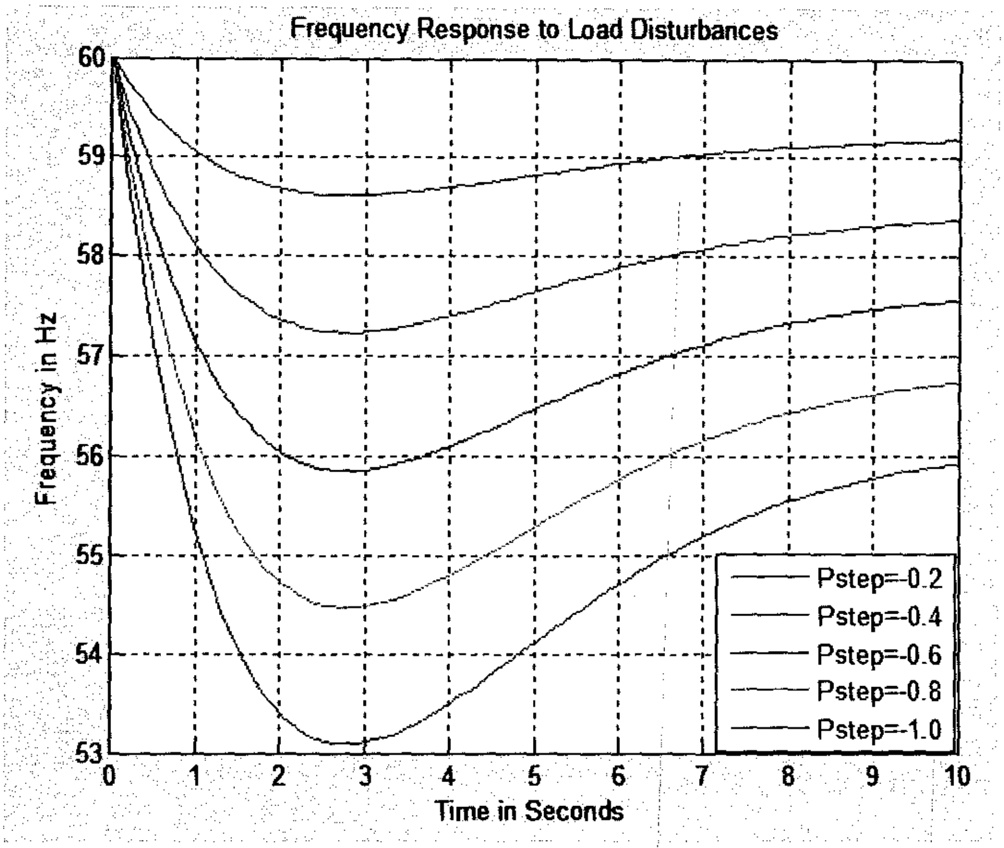


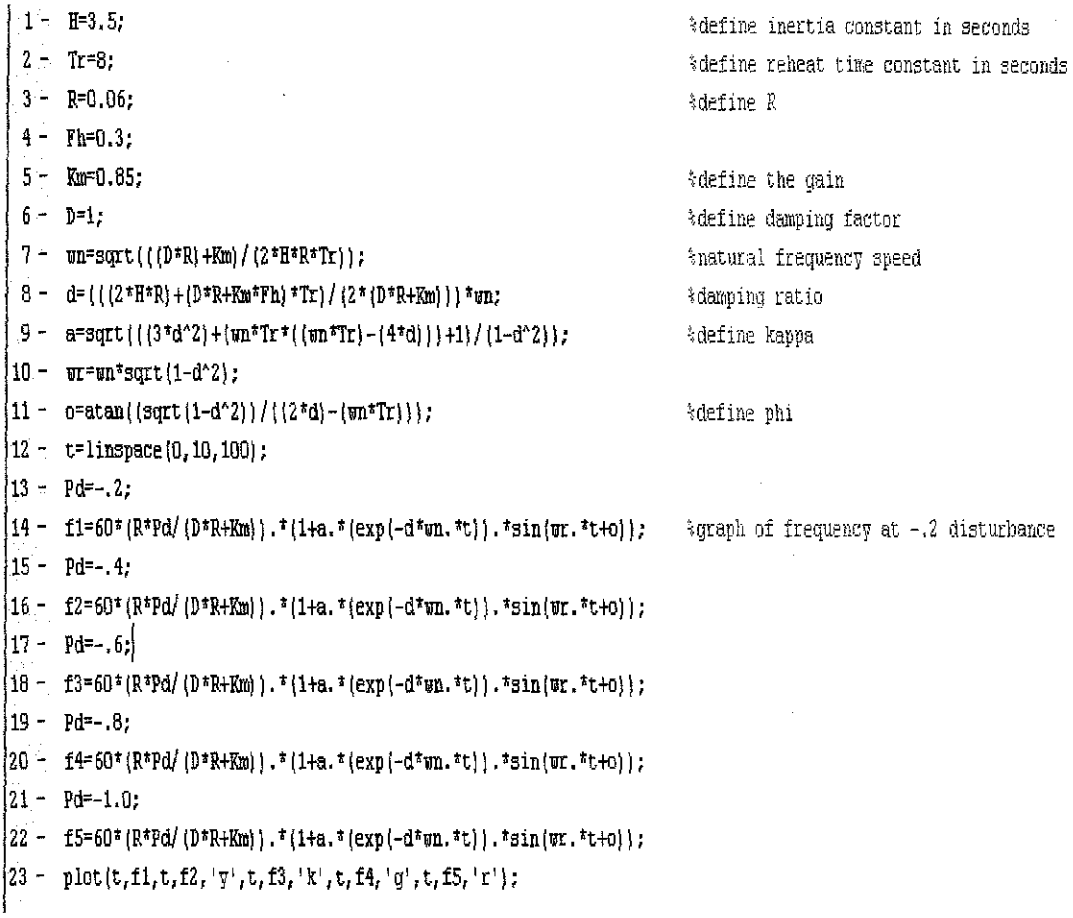
Figure 11 Frequency Response to Load disturbances

In Figure 11 shows the frequency deviations without load shedding. Setting the minimum allowable frequency to 57 hertz, it can be seen that for disturbances greater than about 0.4 per unit the frequency deviation is very likely to drop below 57 Hz set point

As mentioned earlier, it is usually recognized that sufficient load should be shed to limit the frequency decline above 57 hertz in a 60 hertz system. The amount of load shed and the timing of each step of load shedding much be determined.

As shown in the above figure 11, the load shedding scheme should only addresses to disturbances higher than about 0.4 as they are the only disturbances that are able to cause the frequency to fall below the 57 hertz threshold. Disturbances of 0.2 and 0.4 for example, will never reach the frequency set point and therefore, the operators have ample time to remedy the situation

The Matlab code to obtain graphs of figure 11 is shown below:



```
H=3.5;                                                        %define inertia constant in seconds
Tr=8;                                                         %define reheat time constant in seconds
R=0.06;                                                       %define R
Fh=0.3;
Km=0.85;                                                      %define the gain
D=1;                                                          %define damping factor
wn=sqrt(((D*R)+Km)/(2*H*R*Tr));                               %natural frequency speed
d=(((2*H*R)+(D*R+Km*Fh)*Tr)/(2*(D*R+Km)))*wn;                 %damping ratio
a=sqrt((((3*d^2)+(wn*Tr*((wn*Tr)-(4*d)))+1)/(1-d^2));         %define kappa
wr=wn*sqrt(1-d^2);
o=atan((sqrt(1-d^2))/((2*d)-(wn*Tr)));                        %define phi
t=linspace(0,10,100);
Pd=-.2;
f1=60*(R*Pd/(D*R+Km)).*(1+a.*(exp(-d*wn.*t)).*sin(wr.*t+o));  %graph of frequency at -.2 disturbance
Pd=-.4;
f2=60*(R*Pd/(D*R+Km)).*(1+a.*(exp(-d*wn.*t)).*sin(wr.*t+o));
Pd=-.6;
f3=60*(R*Pd/(D*R+Km)).*(1+a.*(exp(-d*wn.*t)).*sin(wr.*t+o));
Pd=-.8;
f4=60*(R*Pd/(D*R+Km)).*(1+a.*(exp(-d*wn.*t)).*sin(wr.*t+o));
Pd=-1.0;
f5=60*(R*Pd/(D*R+Km)).*(1+a.*(exp(-d*wn.*t)).*sin(wr.*t+o));
plot(t,f1,t,f2,'y',t,f3,'k',t,f4,'g',t,f5,'r');
```

4.6.2 Estimation of the amount of load to be shed

To find the estimated amount of load to be shed we make use of the initial slope or rate of change of frequency. Knowing the initial slope we can estimate the size of the disturbance and therefore, the amount of load to be shed.

The following table 5 shows relationship between different disturbances and their corresponding initial slopes as related by equation (3). Note that m_o is the Rate of Change of Frequency at t =0. The maximum deviation, $\Delta\omega_{max}$ has been obtained by finding the minimum value of each graph of figure 11. While f_{min} is the result obtained after adding 60 Hz and $\Delta\omega_{max}$ of each row.

The highlighted row in figure 5 represents the maximum step change of load that can be permitted if the frequency is not to decline below 57 Hz. This step change much be set as the limiting value. Therefore, when the magnitude of the observed initial slope is greater than 3.75 Hz, load shedding much be triggered

Table 5 Initial slope and Maximum Deviation vs Upset

P_{Step}	m_o		$\Delta\omega_{max}$	f_{min}
pu	pu/s	Hz/s	Hz	Hz
-0.2000	-0.0286	-1.7143	-1.3835	58.617
-0.4000	-0.0571	-3.4286	-2.7670	57.233
-0.4337	**-0.0620**	**-3.7500**	**-3.0000**	**57.000**
-0.6000	-0.0857	-5.1429	-4.1505	55.850
-0.8000	-0.1143	-6.8571	-5.5340	54.466
-1.0000	-0.1429	-8.5714	-6.9157	53.084

Let also see the graph corresponding to P_{step} = -0.4337 p.u together with other disturbances greater than that in figure 12.

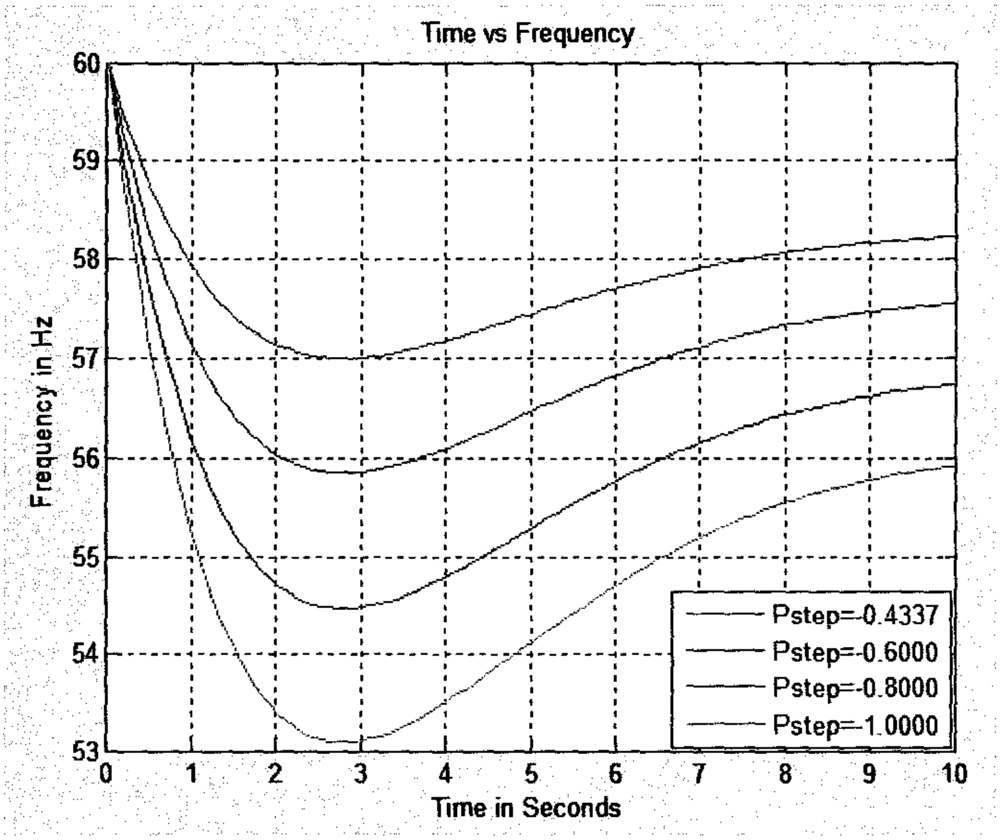


Figure 12 Time vs Frequency graphs comparing maximum allowable disturbance with higher disturbances.

Since the system is linear, we can use the following formula to find the incremental load shed in per unit

$$\frac{P_{Shed}}{2H} = \frac{|P_{Step}|}{2H} - 0.0620 \qquad \frac{per\ unit}{s} \tag{20}$$

Now, since

$$m_o = 60\frac{d\Delta\omega}{dt}\bigg|_{t=0} = \frac{60P_{Step}}{2H} \qquad Hz/s \tag{21}$$

Or

$$P_{Step} = \frac{2Hm_o}{60} \qquad per\ unit \tag{22}$$

From equation (20) and equation (23) we can get the equation of total amount of load to be shed following a disturbance.

$$P_{Shed} = |P_{Step}| - 0.124H = H\left(\frac{|m_o|}{30} - 0.124\right) \quad per\ unit \tag{23}$$

Let assume that a disturbance P_{Step}=-1.0 occurred in the plant. We want to design a protection scheme based on that worse disturbance of the islanded power system. From table 5 we can see that the corresponding initial slope will be -8.5714 per unit so, substituting that value into equation (23) and taking the inertia constant to be 3.5 seconds we find

P_{Shed} =0.5660*1.05 =0.5943 per unit

4.7 Proposed load Shedding Scheme

It is prudent to begin load shedding at a frequency of 59.0 Hz to 59.5 Hz because the relays have a finite time delay so that the actual time at which load is shed will be delayed. Equation (23) would be adequate if we were to shed all the the entire P_{shed} at t=0 which is not prudent. The computed amount of load to be shed is the minimum and it can be considered as static load shed amount that ignores the dynamics of the system frequency decays up to the actual shedding instant. It is recommended to shed load in several steps, with appropriate time delay for each step. Many scholars recommend time delay greater than 20 milliseconds

The size of load to shed in the first step of load shedding is recommended to be haft of the total amount to be shed. Following steps can be of the equal size, preferably 0.1 per unit each In the following scheme the auteur used 0.3 Hz frequency decay.

Table 6 Load Shedding Scheme for 1.0 Per Unit Step Input

Frequency of Load Shedding, Hz	Amount of Load Shed, per unit
59.5	0.2972
59.3	0.1000
58.9	0.1000
58.6	0.0972
Total Load Shed	**0.5660* 1.05= 0.5943**

The scheme in Table 6 has been tested in Matlab as shown in Figure 13

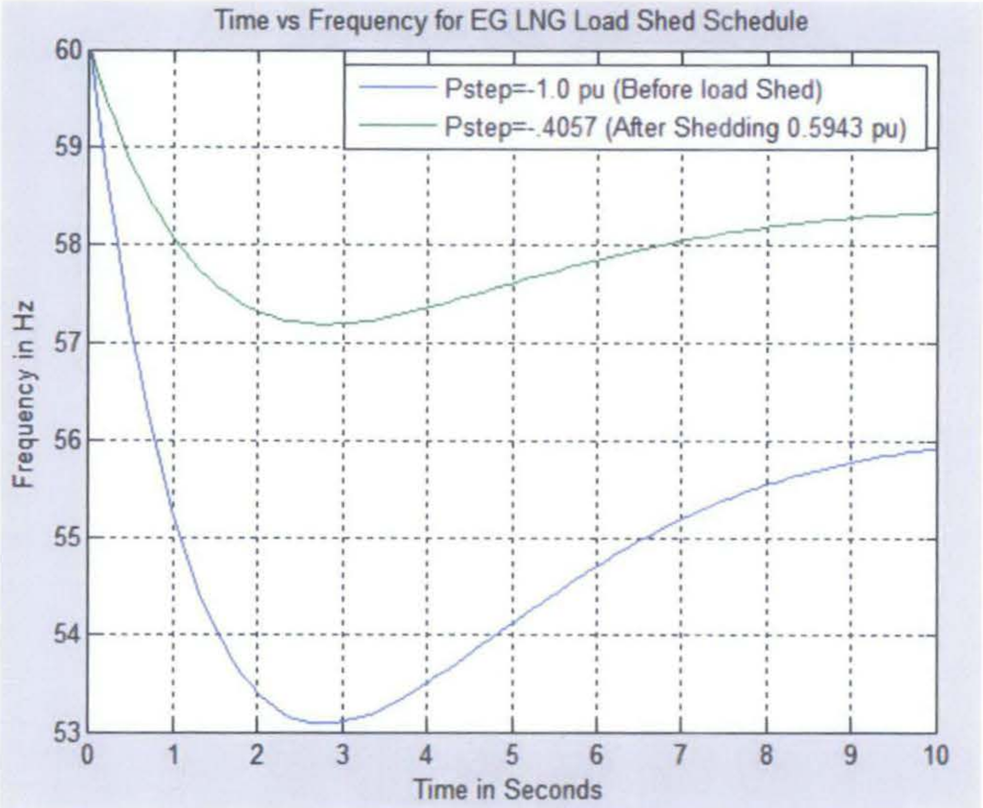


Figure 13 Result of load Shedding according to Adaptive Schedule

4.8 Simple scheme of load shedding design in Matlab

Figure 10 below capture the layout of the simple design implemented in Matlab;

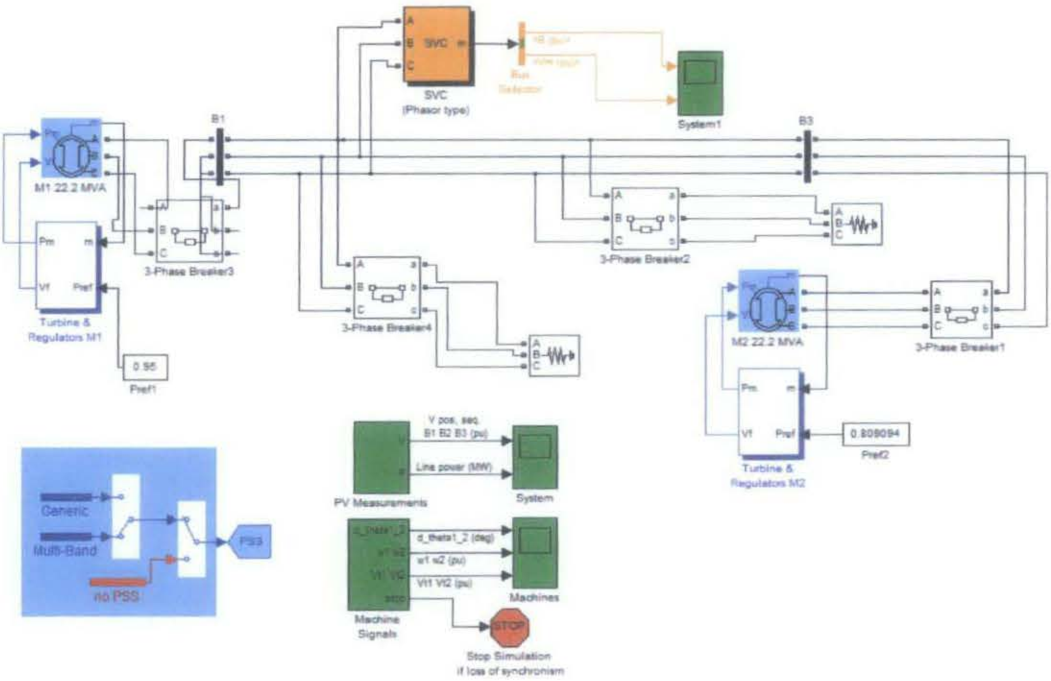


Figure 14 Matlab layout of load shedding scheme simple design

4.9 Simulation results

Figures 11 and 12 present the results obtained during simulation

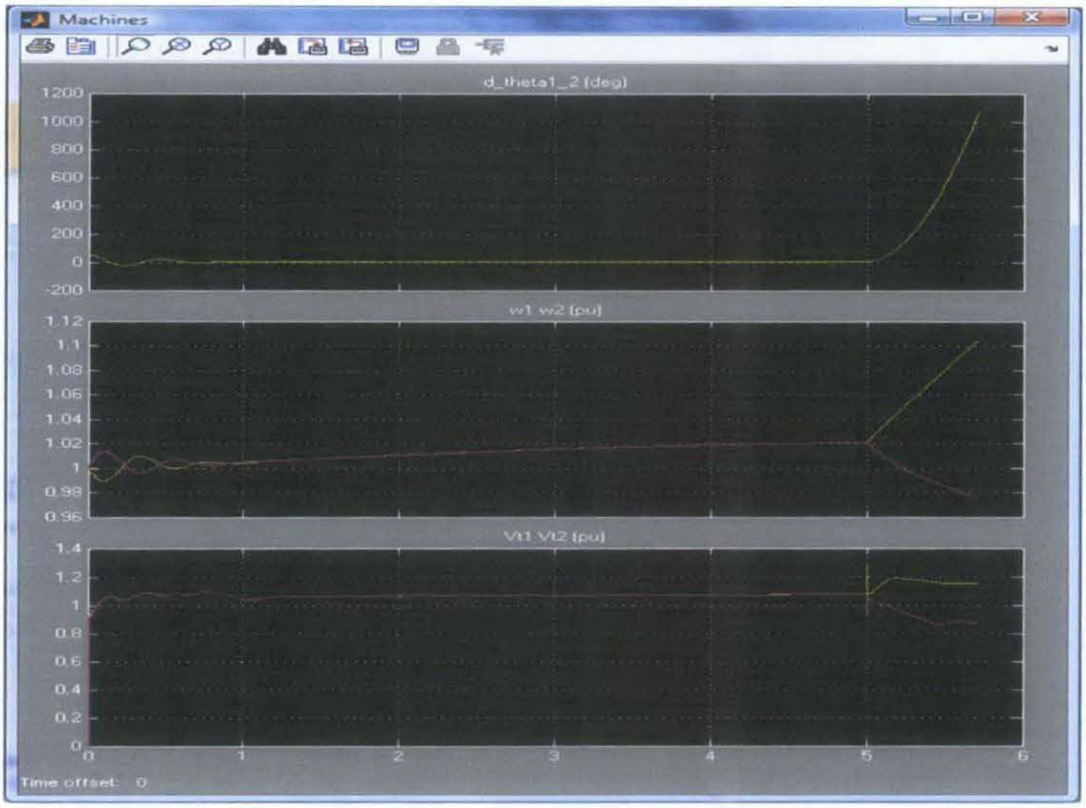


Figure 15 Graphs showing change of frequency of generator after trip

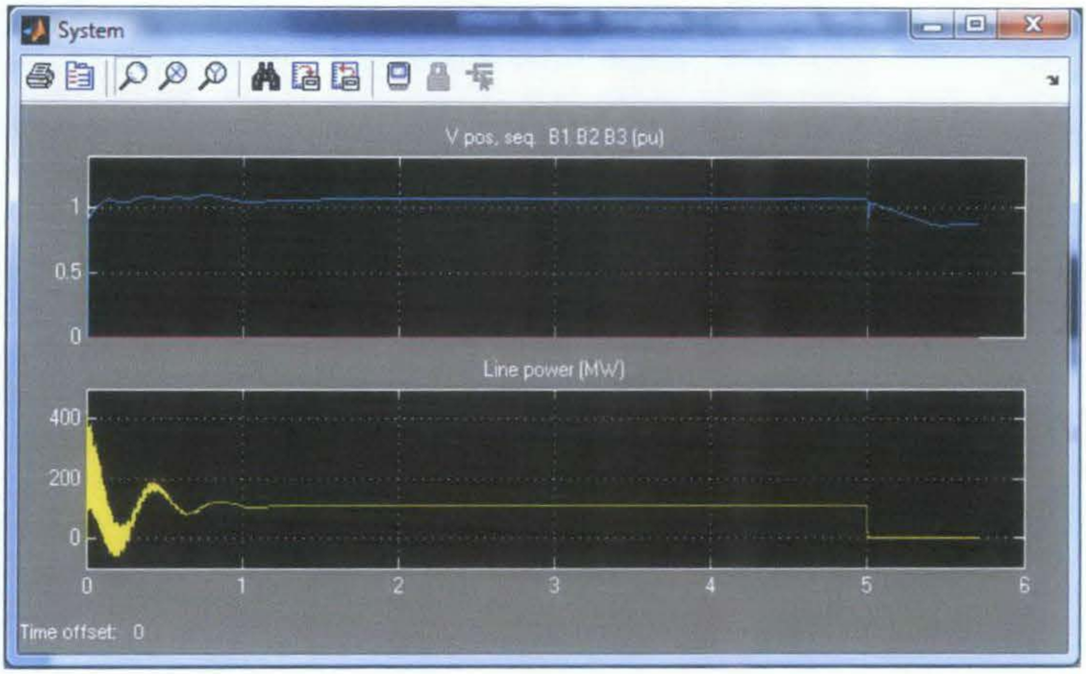


Figure 16 Line power before and after generation loss

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

5.1.1 Getting to know Load Shedding

Load shedding is a strategy of removing load from power system under stress. It is a control methodology setting either voltage or frequency as the control variable. The manipulated variable in that case is the active power demand of customers. As in any control system case, whenever the control variable is bellow or above the set point action of removing load should be taken. It may also de required to add load in some circumstances but this study has limited to the case of Load removal due to excess load or generation deficiency.

There are many ways of implementing load shedding: under-frequency load shedding, if control variable is frequency; under-voltage, if voltage has been considered as control variable.

Under-frequency load shedding can be implemented in two forms: conventional approach and adaptive approach. In conventional approach the load shedding strategy is set offline and it is the same for any kind of disturbance leading to inefficiency. When using conventional approach the system is subject to over-frequency or remain in under-frequency because of inaccuracy of the approach

Adaptive under-frequency however, it is based on the rate of change of frequency and will estimate the amount of load to be shed by considering the severity of the disturbance.

This report proposes the use of Adaptive under-frequency load shedding method in EG LNG plant.

5.1.2 The Proposed Load Shedding Scheme

The author is proposing an automatic load shedding scheme to be implemented in the plant. Rate of change of frequency (ROCOF) relays should be placed at feeders levels where the entire load under relieve are connected. The author suggests the use of distributed load shedding scheme rather than centralized one because in the case of one relay failure, the remaining relays will still be able to handle the load shedding program. In figure 10, the non-red colored feeders and circuit breakers are good candidates to hold ROCOF relays

The relays settings should follow the strategy of table5 in which different disturbances have been analyzed giving the corresponding initial ROCOF and the minimum frequency up to which the wave form can reach. There should be a comparator in the relays so that it can check and compare any given ROCOF at the time with the threshold ROCOF at 57 Hz

We take four steps to stop the worse disturbance case considered in table 6 and the results of the simulation can be found in figure 13. The size of the first step of load shedding is proposed to be haft of the amount of load to be shed while in the remaining steps same size of load can be shed, preferably 0.1 per unit each. A constant frequency decay of 0.3 Hz has been used in the design.

The overall load of the plant has been classified based on plant operation priorities. There we have non-essential load, essential load, crucial load, very crucial load and mandatory load. Mandatory load should never been shed voluntarily.

5.2 Recommendation

The author recommends to do further research for betterment of the topic as it is important to safeward the integrity of the power system.

And appropriate software for simulation is required rather that Matlab. The author did not found it difficult to start shedding load from 59.5 instead of zero. It is not practical to shed load from t=0 but that is want the author found so far. Better approaches can be made with other software. Matlab Simulink was also used to check the behavior of frequency, voltage and phase angle after a sudden disconnection of one of the generators.

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APPENDICES

APPENDIX A

ACTUAL AND PER CENT LOAD DISTRIBUTION IN EQUATORIAL GUINEA LNG PLANT

CONNECTED LOAD AT MAIN SWITCHGEAR 1ESM1-1J041					
CB TAG	**Switchgear tag**	**Substation**	**Actual Load (kW)**	**Per cent Total Load**	**Category**
F4	1ESL1-0F121	Marine	215	0.46	**Non-essential (0.46%)**
F14A	1ESM1-1J041	Main	1895	4.08	**Essential (32.38%)**
F14B	1ESM1-1J041	Main	1895	4.08	
F15A	1ESM1-1J041	Main	1895	4.08	
F1	1ESL1-0B321	Loading	618	1.33	
F2	1ESL1-0B331	Loading	4319	9.31	
F7	1ESM1-1A031	Compressor Area	1584	3.41	
F11	1ESL1-1L021	Propane Condenser	981	2.11	
F12	1ESL1-1L022	Propane Condenser	908	1.96	
F13	1ESL1-1L023	Propane Condenser	936	2.02	
F5	1ESL1-0G321	AGRU	1479	3.19	**Crucial (6.49%)**
F6	1ESM-0G331	AGRU	1533	3.30	
F3	1ESL1-0C122	Water System & Buildings	906	1.95	**Very Crucial (1.95%)**
F8	1ESL1-1J021	Main	872	1.88	**Mandatory**
F9	1ESL1-1J022	Main	804	1.73	
F10	1ESM1-1J031	Main	2240	4.83	

TB	1ESM1-0H051	Main	23334	50.28	**(58.72%)**

APPENDIX B

LOAD DISTRIBUTION OF EQUATORIAL GUINEA LNG PLANT IN PER UNIT KVA OF TWO UNDER STRESS GENERATION CASES

CONNECTED LOAD AT MAIN SWITCHGEAR 1ESM1-1J041								
CB TAG	**Switchgear Tag**	**Actual Load**		**Per Unit Load 52260 kVA Base**		**Per Unit Load 26130 kVA Base**		**Category**
		kW	**Per Cent**					
F4	1ESL1-0F121	215	**0.46**	0.004	**0.004**	0.008	**0.008**	**Non-Essential**
F14A	1ESM1-1J041	1895	**32.38**	0.036	**0.287**	0.073	**0.578**	**Essential**
F14B	1ESM1-1J041	1895		0.036		0.073		
F15A	1ESM1-1J041	1895		0.036		0.073		
F1	1ESL1-0B321	618		0.012		0.024		
F2	1ESL1-0B331	4319		0.083		0.165		
F7	1ESM1-1A031	1584		0.030		0.061		
F11	1ESL1-1L021	981		0.019		0.038		
F12	1ESL1-1L022	908		0.017		0.035		
F13	1ESL1-1L023	936		0.018		0.036		
F5	1ESL1-0G321	1479	**6.49**	0.028	**0.057**	0.057	**0.116**	**Crucial**
F6	1ESM-0G331	1533		0.029		0.059		
F3	1ESL1-0C122	906	**1.95**	0.017	**0.017**	0.035	**0.035**	**Very Crucial**
F8	1ESL1-1J021	872	**58.72**	0.017	**0.521**	0.033	**1.043**	**Mandatory**
F9	1ESL1-1J022	804		0.015		0.031		
F10	1ESM1-1J031	2240		0.043		0.086		
TB	1ESM1-0H051	23334		0.446		0.893		

APPENDIX C

DERIVATION OF LINEAR SYSTEM FREQUENCY RESPONSE EQUATIONS

C.1 Transfer Function.

The transfer function of linear system response model in figure 7 can be obtained following the steps below:

Step 1: Find the closed-loop transfer function of the inner negative feedback

Let

$$G_1(s) = \frac{1}{2Hs}\,;\ H_1(s) = D;\ H_2(s) = \frac{K_m(1 + F_H T_R s)}{R(1 + T_R s)}$$

Then,

$$\frac{\Delta\omega}{P_a} = \frac{G_1(s)}{1 + G_1(s)H_1(s)} = G_2(s) \qquad (c1)$$

Hence, replacing respective expressions of $G_1(s)$ and $H_1(s)$ in equation - following simplifications - the inner transfer function results

$$G_2(s) = \frac{1}{2Hs + D} \qquad (c2)$$

Step 2: finding the transfer function of the model.

To find the transfer function of the system we consider closed-loop transfer function of the outer negative feedback, which is

$$\frac{\Delta\omega}{P_d} = \frac{G_2(s)}{1 + G_2(s)H_2(s)} = G(s) \qquad (c3)$$

Substitution of $G_2(s)$ and $H_2(s)$ in equation (c3) yields

$$G(s) = \frac{\frac{1}{2Hs + D}}{1 + \left(\frac{1}{2Hs + D}\right)\left[\frac{K_m(1 + F_H T_R s)}{R(1 + T_R s)}\right]} \qquad (c4)$$

The above equation can be rearranged to match the general second-order transfer function below

$$G(s) = \frac{{\omega_n}^2}{s^2 + 2\zeta\omega_n s + {\omega_n}^2} \qquad (c5)$$

So,

$$G(s) = \left[\frac{R(1 + T_R s)}{2RHT_R}\right]\left(\frac{2HRT_R}{DR + K_m}\right)\left[\frac{\frac{DR + K_m}{2HRT_R}}{S^2 + \left(\frac{2HR + DRT_R + K_m F_H T_R}{2HRT_R}\right)s + \frac{DR + K_m}{2HRT_R}}\right]$$

Hence

$${\omega_n}^2 = \frac{DR + K_m}{2HRT_R}$$

And

$$2\zeta\omega_n = \frac{2HR + DRT_R + K_m F_H T_R}{2HRT_R}$$

Or

$$\zeta = \frac{2HR + DRT_R + K_m F_H T_R}{4HRT_R {\omega_n}^2}(\omega_n)$$

After substitution of the expression of ω_n^2 and further simplifications, we can write ζ as follows

$$\zeta = \left[\frac{2HR + (DR + K_m F_H)T_R}{2(DR + K_m)}\right]\omega_n$$

Considering the above parameters the equation of G(s) results

$$G(s) = \frac{\Delta\omega}{P_d} = \left[\frac{R(1 + T_R s)}{DR + K_m}\right]\left(\frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}\right) \qquad (c6)$$

Finally, the model output, which represents the variation of system frequency in per unit of connected generation MVA base, is

$$\Delta\omega = \left(\frac{RP_d}{DR + K_m}\right)\left[\frac{(1 + T_R s)\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}\right] \qquad (c7)$$

C.2 Finding time-domain expression of Δω resulting from an step input, P_{step}

$$\Delta\omega = \left(\frac{RP_{step}}{DR + K_m}\right)\left[\frac{(1 + T_R s)\omega_n^2}{s(s^2 + 2\zeta\omega_n s + \omega_n^2)}\right] \qquad (c8)$$

To convert equation (c8) into time domain we only consider the last part due to simplification proposes and the fact that the first part is a constant.

Using partial fraction-expansion we can write

$$\frac{(1 + T_R s)\omega_n^2}{s(s^2 + 2\zeta\omega_n s + \omega_n^2)} = \frac{1}{s} + \frac{\omega_n^2 T_R - 2\zeta\omega_n}{s^2 + 2\zeta\omega_n s + \omega_n^2} - \frac{s}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad (c9)$$

Rearranging right hand side (RHS) of (c9) we get

$$\mathrm{RHS} = \frac{1}{s} + \frac{\omega_n{}^2 T_R - 2\zeta\omega_n}{(s+\zeta\omega_n)^2 + \left(\omega_n\sqrt{1-\zeta^2}\right)^2} - \frac{s}{(s+\zeta\omega_n)^2 + \left(\omega_n\sqrt{1-\zeta^2}\right)^2} \qquad \text{(c10)}$$

Setting $\omega_r = \omega_n\sqrt{1-\zeta^2}$ and rearranging (c10) once again results

$$\mathrm{RHS} = \frac{1}{s} + \left(\frac{\omega_n T_R - 2\zeta}{\sqrt{1-\zeta^2}}\right)\left[\frac{\omega_r}{(s+\zeta\omega_n)^2 + \omega_r{}^2}\right] - \frac{s}{(s+\zeta\omega_n)^2 + \omega_r{}^2} \qquad \text{(c11)}$$

The Inverse Laplace Transform of the last equation yields

$$RHS(t) = \left\{1 + e^{-2\omega_n t}\left[\left(\frac{\omega_n T_R - 2\zeta}{\sqrt{1-\zeta^2}}\right) sin(\omega_r t) - cos(\omega_r t)\right]\right\} u(t) \qquad (c12)$$

The last expression can still be simplified by recalling sum of sine and cosine functions identity. From trigonometry we know

$$\mathrm{A} sin(\omega_r t) + \mathrm{B} cos(\omega_r t) = \kappa sin(\omega_r t + \varphi) \qquad (c13)$$

Where,

$$\kappa = \sqrt{\mathrm{A}^2 + \mathrm{B}^2}$$

And

$$\varphi = tan^{-1}\left(\frac{\mathrm{B}}{\mathrm{A}}\right)$$

From equation (c12), setting

$$\mathrm{A} = \frac{\omega_n T_R - 2\zeta}{\sqrt{1-\zeta^2}} \, ;$$

$$\mathrm{B} = -1$$

Then,

$$\kappa = \sqrt{\frac{3\zeta^2 + \omega_n T_R(\omega_n T_R - 4\zeta) + 1}{1 - \zeta^2}}$$

And

$$\varphi = tan^{-1}\left(\frac{\sqrt{1-\zeta^2}}{2\zeta - \omega_n T_R}\right)$$

Finally, after conversions equation (8) becomes

$$\Delta\omega(t) = \left(\frac{RP_{step}}{DR + K_m}\right)\left[1 + \kappa e^{-\zeta\omega_n t} sin(\omega_r t + \varphi)\right]u(t)$$

APPENDIX D

FYP 1 PROJECT GANTT CHART

No.	Task	Week																	
		1	2	3	4	5	6	7	8	9	10	M.B.	11	12	13	14	15	E.W.	
	Topic Selection											Mid-Semester Break						Examination Week	
1	Title Selection, Submission and Allocation	🟨	🟨🔵																
	Preliminary Research Work																		
2	Definition of objectives, purpose and scope of study			🟨	🟨🔵														
	Project Planning																		
3	Work Breakdown Structure and Scheduling				🟨	🟨	🟨	🟨	🟨										
4	Process Flow						🟨	🟨	🟨🔵	🟨	🟨		🟨	🟨	🟨	🟨	🟨		
	Research Work																		
5	Find definition and methods of load shedding					🟨	🟨	🟨						🔴					
6	Approaches of load shedding schemes implementation					🟨	🟨	🟨	🟨	🟨	🟨		🟨	🟨	🟨🔵	🟨	🟨		
7	Analyze and pick the suitable scheme for EG LNG Plant and look for required data of the Network												🟨	🟨	🟨	🟨🔵			🔴

🟨 Process 🔵 Report 🔴 Presentation

APPENDIX E

FYP 2 PROJECT GANTT CHART

No.	Task	Week																
		1	2	3	4	5	6	7	M.B.	8	9	10	11	12	13	14	E.W.	
	Project Work Continue								Mid-Semester Week								Examination Week	
1	Calculations of Plant System Generation and Load	🟨	🟨	🟨														
2	Submission of Progress Report 1				🔵													
	Project Work Continue																	
3	Plant System Load Categorization				🟨	🟨	🟨	🟨										
4	Submission of Progress Report 2									🔵								
5	Redrawing of Plant One Line Diagram						🟨	🟨										
	Project work continue																	
6	Develop System Frequency Response Model									🟨	🟨	🟨	🟨					
7	Simulations of the Model											🟨	🟨	🟨				
8	Poster Exhibition												🔴					
9	Submission of Dissertation (soft bound)														🔵			
10	Oral Presentation																	🔴
11	Final Revision of Dissertation														🟨	🟨		
12	Submission of Project Dissertation (Hard Bound)																	🔵

🟨 Process　🔵 Report　🔴 Presentation