Tanta University
Faculty of Engineering
Electrical Power and Machines Engineering Department

ISLANDING SCENARIOS FOR HIGH RELIABLE OPERATION OF DISTRIBUTION NETWORKS

Thesis submitted in partial fulfillment of the requirement for the degree of
Master of Science in Engineering
(Electrical Power and Machines Engineering)

By

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May 2019

To those who inspired it

and will not read it

ABSTRACT

Islanding is considered important problem that faces distributed generation. This problem occurs when the protection system takes a correct action to disconnect the fault as a result of that new isolated system is formed. This study introduces a methodology for performing intentional islanding with maximum possible benefits for distribution systems. The methodology is based on an advanced load shedding algorithm to achieve load generation balance and apply a control strategy to ensure a smooth transition from normal mode to island mode with high load power quality. Generally, the load shedding algorithm is applied to improve the reliability by serving maximum number of customers. Investigation of the dynamic behavior of the distribution network during transition due to intentional islanding is a main concern in this thesis. When operating in the island mode, the local supervisory control system can modify the generator frequency controller and voltage controller to guarantee high power quality for the new isolated system. In addition, it is suggested to assess the small signal stability of new islands to evaluate their performance and give priority among different alternatives. Small signal stability study is introduced for each island to check the stability for the new islands. IEEE 33-bus system is taken as a case study to ensure the effectiveness of the introduced methodology. The analysis is performed for a case study with optimal DG locations and sizes. NEPLAN software is used for dynamics and small signal stability investigations.

SUMMARY

Due to the increase in load demand, the utilization of DG technology became a necessity in recent years. DG penetration increases power system reliability, reduces power losses and enhances the voltage profile. However, there are drawbacks facing the insertion of DG in power systems such as malfunctioning of protection scheme and loss of mains (islanding). The traditional precautions after islanding process are to disconnect distributed generation (DG) to ensure safe operation. However, disconnection of DGs reduces the island reliability and security. Many of the DG owners prefer to control the islanding process and follow certain constraints and regulations for the resulting isolated system, while maintaining the DGs to supply the local load demand. Distribution systems are equipped with monitoring and control systems that help to detect islanding states and create intentional island configurations.

The aim of this study is to increase system reliability of distribution systems via ensuring feeding electricity for most customers according to a priority database. At the same time, it is important to adapt the control behaviour and enhance the dynamics of intentional islands. The first step is to select the optimal allocation of the DG in the case study taking into account the possibility of intentional islanding. The second step is to choose the optimal island configurations according to system topology, load shedding limit and DG penetration level. The third step is to develop a load shedding algorithm that identifies the suitable loads which can be supplied from local units in the island. Furthermore, the load shedding algorithm has to facilitate the transition moment and create more stable islands. The fourth step is to monitor the dynamics of transition moment to island mode. Finally, it is important to examine the quality of the power (voltage and frequency) delivered to the load and modify the control settings if needed. The small signal stability analysis is provided for different island configurations to give priorities for the operator when there are different alternatives to be selected. Thus, it will be possible to maintain the service to important loads and decrease the total economic losses even with load variations.

ACKNOWLEDGMENTS

All praises and thanks are to Allah, the Lord of the world for helping me to accomplish this work.

I seize this opportunity to express my deep and sincere gratitude to my supervisors Prof. Ahmed Refaat Azmy and Dr. Hossam Abd el-Ghany, for their support and guidance throughout my work in this thesis. Not only did they promote my research work with their scientific knowledge and constructive criticism, but they also gave me the moral support I needed during this stressful time.

My gratitude is also extended to the Electrical Power and Machines Engineering Department staff for their help, support and encouragement.

Last but not least, I would like to thank my parents, my brother Mahmoud, my sister Asmaa and my wife Hanan for their encouragement and help during the research period.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

Symbol	Description	Unit
f	Frequency of electromagnetic radiation	Hz
P	Active power	MW
P_{conn}	Connected active power	MW
Q	Reactive power	Mvar
R	Resistance	Ω
S	Apperant power	MVA
t	Time	s
V	Voltage	V
X_l	Reactance	Ω
α	Real part of the Eigenvalue	
β	Imaginary part of the Eigenvalue	
λ	Eigenvalue	

Abbreviations

Abbreviation	Description
AC	Alternating current
AVR	Automatic Voltage Regulator
DC	Direct current
DCS	Distributed Control System
DER	Distributed Energy Resource
DG	Distributed generation
EPS	Electric Power System
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
LS	Load Shedding
MIC	Monitoring, Information exchange, and Control
PCC	Point of Common Coupling
LSA	Proposed Load Shedding Algorithm
PMU	Phasor Measurement Unit
PV	Photovoltaic
SCADA	Supervisory Control and Data Acquisition
WT	Wind turbines

CHAPTER 1
Introduction

1.1 Motivation

In the modern world, electricity has become the lifeblood of civilization. The quick escalating demand and the high dependability on electricity necessitate reliable operation of the utilities especially for industrial loads. Generally, the continuity of providing electrical power is vital. To achieve the continuity of supplying electrical power to customers, researches recommend many solutions such as upgrading old utilities, converting the traditional systems to smart systems via installing automation equipment [1], and installing distributed generation (DG) near load centers. Adding new DGs increases the power system reliability [2]. If these DGs are dependent on renewable energy resources such as Photovoltaic (PV) and wind turbines (WT), other benefits are gained such as reducing CO_2 emissions.

The large-scale investments, such as cement factories, install DGs to generate their demand locally due to the high increase in electricity tariffs especially when they are far from the main utility system [3]. Installing DGs that depend on renewable energy is very expensive and, hence, isolated industries depend on reliable energy sources such as diesel, micro-turbines or small gas turbines [3]. Integrating these DGs with the grid increases the reliability of the entire power system. However, adding DGs to distribution systems has many drawbacks [4]. One of the main drawbacks facing this procedure is the possibility of islanding occurrence. That is, a part of the distribution system is isolated from the main grid network forming a new island. Islanding is categorized into intentional and unintentional types [5].

Therefore, it is important to develop new mechanisms to facilitate intentional islanding process and guarantee the continuity of supplying important loads in the local island. By achieving these objectives, the reliability of the distribution system will be increased.

1.2 Distribution System Reliability

According to IEEE (PES definition) [6], reliability of power systems is defined as: “Reliability is the probability of a device or a system performing its function adequately, for the period of time intended, under the operating conditions intended”. To be more specific, ref. [7] introduces another definition to power system reliability which is “quantifying the ability of a power system to provide an adequate and secure supply of electrical energy”.

Reliability is based mainly on adequacy and security [8]. Adequacy is defined as “A measure of the ability of the power system to supply the aggregate electric power and energy requirements of the customers within components ratings and voltage limits, considering planned and unplanned outages of system components”. Adequacy refers to “The capability of the power system to supply the load in all the steady states in which the power system may exist considering standards conditions” [8]. As can be understood, the adequacy is related to the existence of generating power within the system to satisfy the load demand all the time [8]. Security is the ability of the power system to withstand sudden disturbances [8].

The reliability of the power system is a statistical problem [8]. Most of the probabilistic techniques for reliability assessments are with respect to adequacy assessments. There are three hierarchical levels for reliability analysis. These levels are: reliability assessment of “generation”, “generation and transmission” and “generation, transmission, and distribution”. Reliability has five **major indices** [9] as indicated in Table 1-1.

Table 1-1: Reliability Indices

Index Term	Abbreviation	Short note
System Average Interruption Frequency	SAIFI	$\frac{\mathbf{Total\ number\ interruptions}}{\mathbf{Total\ number\ of\ customers}}$
System Average Interruption Duration	SAIDI	$\frac{\mathbf{customer\ interruption\ durations}}{\mathbf{Total\ number\ of\ customers}}$
Customer Average Interruption Frequency	CAIFI	$\frac{\mathbf{Total\ number\ of\ customer\ interruptions}}{\mathbf{Total\ number\ of\ customers\ interrupted}}$
Customer Average Interruption Duration	CAIDI	$\frac{\mathbf{Customer\ interruption\ durations}}{\mathbf{Total\ number\ of\ customer\ interruptions}}$ or $\frac{\mathbf{SAIDI}}{\mathbf{SAIFI}}$
Customer Total Average Interruption Duration	CTAIDI	$\frac{\mathbf{Customer\ interruption\ durations}}{\mathbf{Total\ number\ of\ customers\ interrupted}}$

All the mentioned indices in Table 1-1 measure interruptions of the network (hours or times). In conclusion, decreasing the duration of interruptions increases the reliability of the distribution system [10]. One of the most important benefits from adding DGs in the system is the increase of adequacy of the distributions systems [10].

1.3 Distributed Generations (DGs)

In the last decade, technological innovations and changes in economic and regulatory environments have resulted in a renewed interest for the distributed generation [11]. DG, as a concept, is not new because the first power station was a small generating unit used to supply local loads and, thus, it could be commonly called DG.

Most world countries, such as China and USA, are suffering from pollution and greenhouse gases. The utilities encourage customers to increase the dependency on renewable energy sources, where most of the modern DGs are based on renewable energy resources. The DGs technology commonly uses DC systems because these systems use energy storage and power electronics in their operations [12].

Ref [11] listed five major factors that contribute to this evolution, i.e., developments in distributed generation technologies, constraints on the construction of new transmission lines, increased customer demand for highly reliable electricity, the electricity market liberalization and concerns about climate changes [11].

1.3.1 DG definition

Because of different governor regulations, the definition and size of DGs are different from one country to another. For example, in the United Kingdom, the turbine must be less than 100 MW to be considered as a DG [13]. In Germany, the local utility built a 300 MW unit to provide heat and electricity that are consumed locally and, so, this unit is considered as a DG. In literature, many terms and definitions are used regarding DG [13]. Table 1-2 describes different definitions of the DG.

There are many terms that are used to express this technology or this type of generation. As an example, in Anglo-American, the term “Embedded generation” is used, while the term “Dispersed generation” is used in North America countries and the term “Decentralized generation” is used in Europe and part of Asia. Some authors define generation between 1 kW and 1 MW as the dispersed generation. The term embedded generation seems to be more appropriate to describe the DG whose power is consumed locally [13]. The DGs can be categorized according to the type and rating. Some authors recommend the categories shown in Fig 1-1.

Table 1-2: Definition of Distributed Generation [14]

Source	Definition
Distributed Power Coalition of America (DPCA)	“Any small-scale power generation technology that provides electric power at a site closer to customers”
International Conference on High Voltage Electric Systems (CIGRE)	The distributed generation is 1. Not centrally planned 2. Usually connected to the distribution network 3. Smaller than 50 or 100 MW
International Energy Agency (IEA)	“The distributed generation is generating plant serving customers on-site or providing support to distribution level voltage”
US Department of Energy (US. DOE)	“Distributed generation small, modular electricity generators sited close to the customer load can enable utilities to defer or eliminate costly investments in transmission and distribution (T&D) system upgrades, and provides customers with better quality, more reliable energy supplies and a cleaner environment”
Institute of Electrical and Electronic Engineers (IEEE)	“Sources of electric power that are not directly connected to a bulk power transmission system and the DR includes generator and energy storage technologies”
American Gas Association (AGA)	“Strategic placement of small power generating units (5 kW to 25 MW) at or near customer loads”

Fig 1-1: DGs Categories According to Size [13].

1.3.2 DG Types

The objective of power system operation is to supply the load demand at all locations within the power system economically and reliably as possible. The traditional power system is based on centralized power stations such as steam, gas, hydro and nuclear power plants [15]. The DG technology has been appeared due to the drawbacks of centralized stations. Currently, many DG technologies are available in the market and few types are still in the research and development stage [15]. The DGs, which are currently available in the market, are reciprocating engines, micro-turbines, combustion gas turbines, fuel cells, photovoltaic and wind turbines. Each of them has its own befits and limitations. Fig 1-2 indicates examples of DGs types.

1.3.3 The advantage of the DGs

Several published papers [16] confirm the feasibility of adding distributed DG in electrical distribution networks. Moreover, many researchers increase the benefits of these units by selecting the optimal locations of DGs to improve the performance of distribution systems [17]. There are many advantages gained from adding DG to the distribution system. This section details some of these advantages.

1. DG will reduce loadings on substation power transformers during peak hours and, thereby, extending the useful life of these equipment and deferring planned substation upgrading.
2. Utilizing DG units reduces the necessity to build new transmission and distribution lines or to upgrade existing ones.
3. Utilizing DG units reduces transmission and distribution line losses and improves power quality and voltage profile of the system.

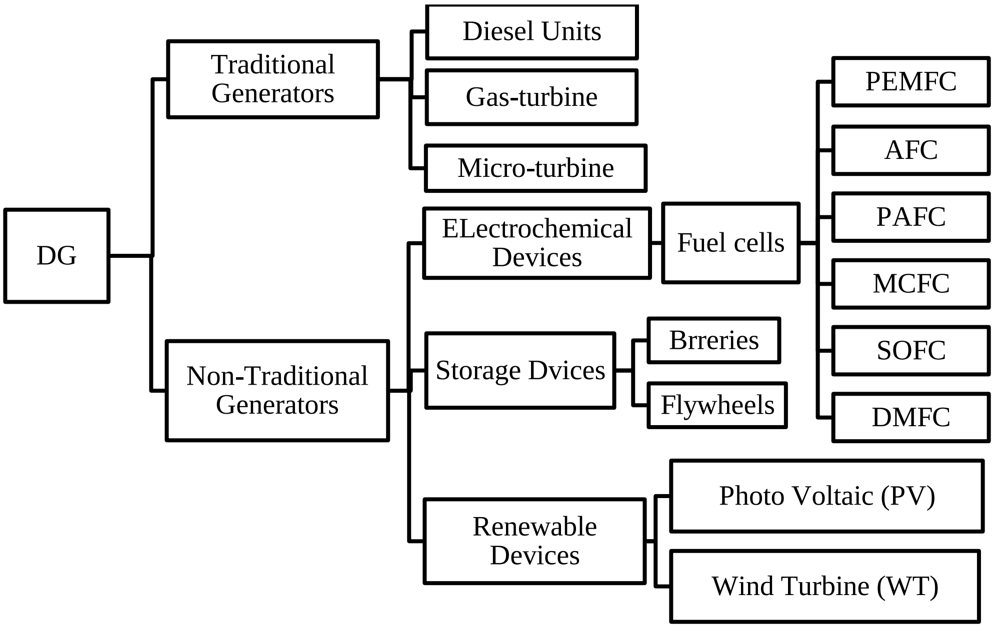


Fig 1-2: Varies Types of DGs in Power System

1.3.4 Challenges facing the DG

There are many challenges facing the insertion of distributed generation in the electric utilities [18]. The following points summarize some potential problems that face DG technologies.

1. One of the major challenges that face the DG utilization is the relatively high capital costs per kW of installed power compared to large central plants. The financial cost problem exists because the technologies used in the DG fabrications are expensive. For instance, fabrication of efficient solar cells [19], large-scale wind farms [20] or efficient fuel cells [21] need a large amount of money in the research stages and in the design stage.
2. The second important problem that is facing the DG insertion is the difficulty of controlling the system frequency after the insertion of the DG.

3. The relation between DG and power quality is an ambiguous one. Regardless of the advantages gained of adding DG to the distributed network, the abovementioned drawbacks regarding system voltage and frequency represent the harmful effect of DG insertion on the power quality.
4. The disadvantage of inserting distributed units on the protection schemes operations is stated as the follows:
    a. Changing power flow affects the short-circuit level in the distribution system and, so, the protection relays mal-operate. In this case, the directional overcurrent protection must be used [22].
    b. The existence of automatic recloser in case of the DG could cause damage to the equipment.
5. Islanding or loss of mains is also a challenge that faces the DG penetration. Unplanned islanding situations affect the safety of human and equipment. Damage may occur with any attempt to reconnect the island with the distribution system as mentioned earlier. The following section will explain this phenomenon in detail.

1.4 Concept of Islanding

Loss of mains, or islanding, means that a portion of the electrical system is isolated from the main grid intentionally or unintentionally. So, islanding can be classified into two types: intentional and unintentional islanding [5, 17].

1.4.1 Unintentional islanding

Unintentional islanding means that the system is divided into subsystems when protective relaying detects abnormal conditions and takes corrective action to isolate the faulty part forming small systems or islands.

The Distributed Energy Resource (DER) may not be suited to control the voltage and frequency of the isolated system. This means that the power quality cannot be guaranteed by the utility. The voltage and frequency can go out of range that could destroy the power system equipment. Even if the DER can control voltage and frequency, the dispatch center of the utility may not be able to supervise the DG.

The first precaution to overcome the drawbacks of unintentional islanding is to detect the islanding condition. Then, the DG must be disconnected until the fault is fixed and the current returns to flow. Now, the DG can be resynchronized again with the system [23].

The main philosophy of detecting an islanding situation is to monitor the DG output variables (voltage and frequency) and system variables and decide whether an islanding situation has occurred from the changes in these variables. Islanding detection techniques can be divided into remote and local techniques, where local techniques can further be divided into passive, active and hybrid techniques as shown in Fig 1-3.

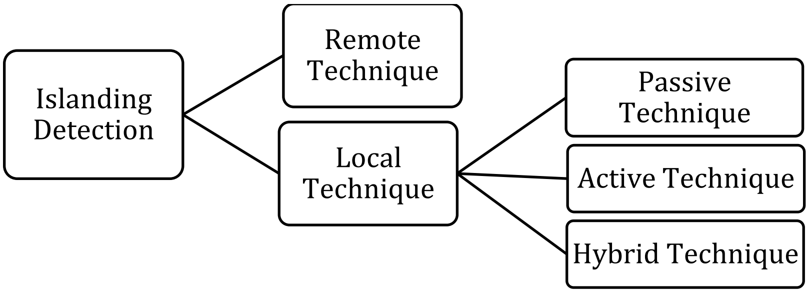


Fig 1-3: Islanding Detection Methods

1.4.2 Intentional islanding

The intentional islanding means that the network operator decides to divide the distribution system into small parts because of a significant disturbance or schedule maintenance [24]. In this case, the intentional islanding is planned in advance and the system and equipment are designed to manage the situation. The DER has to be well suited to control voltage and frequency in the islanded grid. Intentional islanding often exist in industrial plants, where the process has surplus energy that can be used to produce electricity. Examples are found in paper mills, sugar mills, cement factories, oil fields and fertilizing factories that are often capable of producing a large part of their electricity needs internally. During thunderstorms or other adverse weather situations, these plants can be switched to local production of electricity and isolate themselves from the surrounding grid. By performing this islanding, the risk of disturbances due to lightning strokes and other faults affecting the vulnerable process is limited. This type of islanding requires the system to be equipped with monitoring, information exchange, and control (MIC) equipment. Thus, it reduces the restoration time and decreases the financial loss [25].

1.4.2.1 Intentional islanding benefits

Disconnecting DGs causes economic losses since the DGs mainly depend on renewable energy resources [26, 27]. Many system supervisors operate the new island as a standalone system. This way of control increases the system reliability and security and guarantees service continuity for important loads [28]. Intentional islanding has many benefits such as [24, 27]:

1. Improving reliability by providing energy to the islanded portion of the electric power system during abnormal conditions or disturbances
2. Decreasing the power system restoring time and cost
3. Supplying the island at acceptable power quality regardless of the status of the main network
4. Maintaining supplying energy to important customers

1.4.2.2 Islands Types

According to IEEE standard [27], there are many types of islands such as facility island, secondary island, lateral island, circuit island, substation island, substation bus island, and adjacent circuit island [27]. Fig 1-4 indicates these types.

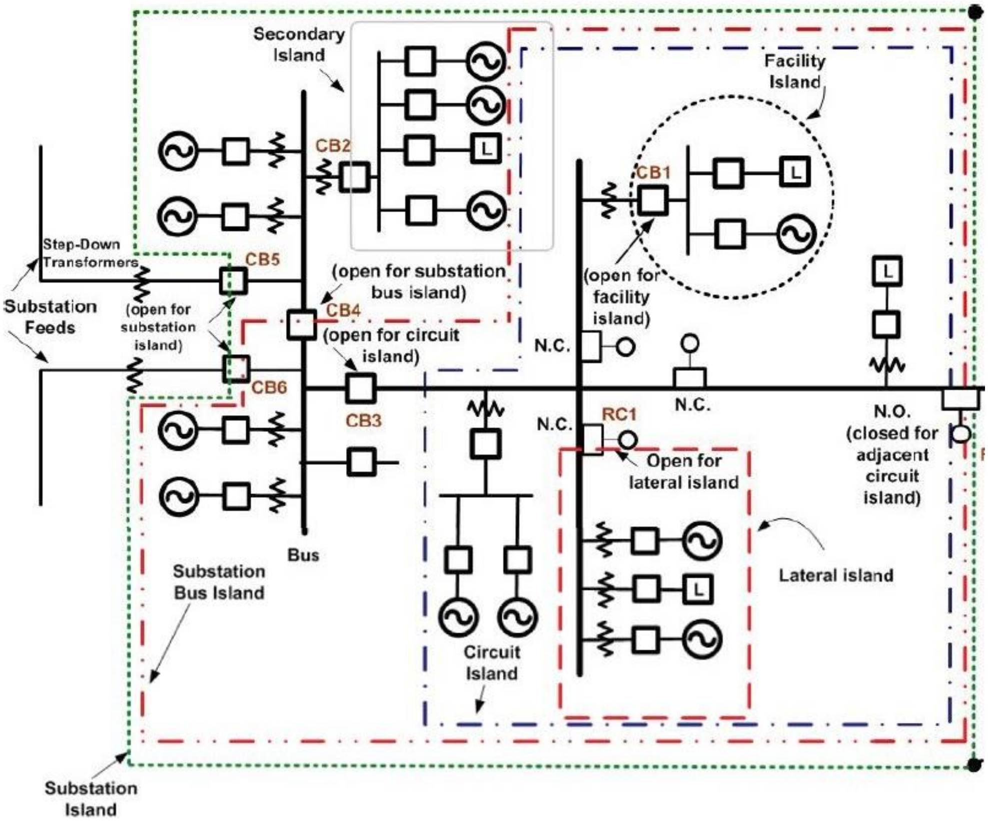


Fig 1-4: Island Types [27]

For creating a new island, the following consideration must be applied [27].

1. The generator rating must be larger than load demand or a load shedding strategy is applied to disconnect the loads to maintain power balance.
2. The voltage and frequency level must be within allowed levels.

3. The voltage and frequency control strategies could be modified when needed to ensure the overall stability.

1.5 Load Shedding Technique

The power system is designed for transmitting the power from generation area to load locations under normal conditions and the system should withstand contingency conditions [29]. One of the ways to decrease the effect of the contingency problems is to disconnect the less important loads (load shedding). Load shedding means deliberately disconnecting loads to ensure a good power quality for remaining part of the power system [29]. This disconnection could be either based on voltage level or frequency level of the system to prevent all system blackout. So, the load shedding is classified into two categories:

1. Undervoltage load shedding (UVLS)
2. Under-frequency load shedding (UFLS)

1.5.1 Undervoltage load shedding (UVLS)

The under-voltage load shedding is that scheme which disconnects some of the loads to prevent voltage collapse and ensure the voltage stability in the system. For these types, the system must be monitored by MIC. The main factors affecting the voltage stability or causing voltage collapse are [29]:

1. Transmission system limitation
2. Load behavior, including load tap changer performance
3. The influence of protection and control systems

1.5.2 Under-frequency load shedding (UFLS)

Unlike UVLS, the under frequency load shedding (UFLS) is that type of schemes that disconnects the load to maintain the frequency in the limited range and prevent frequency collapse, which can lead to a cascading outage.

UFLS is defined as a coordinated set of controls, which results in the decrease of electrical loads in the power system [30].

The objective of an under-frequency load shedding scheme is to quickly recognize generation deficiency within any system and automatically shed a minimum amount of load. At the same time, it provides a quick, smooth and safe transition of the system from an emergency situation to a post-contingency condition such that a generation-load balance is achieved and the nominal system frequency is restored [30].

1.6 Literature Review and Background

Many attempts are recorded to operate a part of a certain system as an isolated system to achieve economic and technical benefits [26, 31]. In this case, the system must be monitored to guarantee successful islanding transition with achieving a power balance between the generation and the load. In many situations, the balance can be achieved via load shedding. After the transition to the island state, the stability of the island must be maintained under small or large disturbances. Therefore, these considerations must be taken into account in the planning stage [26].

In [26], an economic study is introduced for intentional islanding, where some aspects related to the deregulated market are clarified. It is concluded that the system is split during islanding and each island will have its own market price according to a non-competitive situation. In this study, the economic effect of disconnecting the DG is not taken into consideration.

A comparison between distributed control and supervisory control is introduced in [32]. The authors also introduced Micro-Grid Management Systems (MGMS) and control functions such as voltage control, frequency control, operation cost optimization and other protective actions. This reference introduced the actual timing for islanding before the protection system trips the local DG. The timing for each function is detailed in hierarchical order and the authors also clarified the differences between each function. These functions are realized through either a centralized or a distributed MGMS framework.

A droop control method is introduced in [33], where an intelligent control method is introduced using the Global Positioning System (GPS). The control system in [33] described the relationship between the active and reactive power with voltage and frequency. Authors of [33] showed the relationship between the P-Q circle of a DG unit and P-f and Q-E droops. This control wise, with two droops, enhanced the overall stability of the controller. But in this paper [33], the stability[33][33][33][32][31][30][29] is investigated for the radial system only.

Authors in [31] introduced a control scheme to enhance intentional islanding. In this work, the control for inverter-based DG and the conditions for transition to island state were the limitations of voltage and frequency control. Another control strategy is introduced in [28] for inverter-based DG. These controllers did not introduce a solution for power mismatch between the generators and loads or the penetration levels for DGs. Authors in [34] introduced a load shedding mechanism to control the intentional islanding operations without considering DG penetration level or percentage load shedding. Also, authors of [35] suggested some factors for assessing the successful island operation. The study in [36] considers reliability assessment of islands.

Two control strategies for islanding are discussed in detail in [24, 31]. However, the quality of the supplied power is not considered in these studies. Another control strategy is introduced in [28] and [37] without considering load shedding to achieve the balance between the loads and the generated power. A load shedding algorithm has been discussed in [38, 39] but the authors did not introduce a validation for this load shedding on test systems.

The applications of load shedding in the distribution system are discussed in [40]. This study did not test the load shedding in dynamic transition and did not introduce a way for its implementation in real situations.

1.7 Thesis Objectives

The main objectives of the thesis can be summarized as follows:

1- Proposing general framework that enables the intentional islanding for the distribution systems

2- Increasing the flexibility for decision-making by the system operator by introducing many scenarios with priorities for the islanding process

3- Evaluating the success of the load shedding algorithm to provide acceptable dynamic behaviour during the transition moment.

4- Evaluating the small signal stability for all possible cases to give priorities for different island alternatives.

1.8 Thesis Organization

In addition to **chapter 1**, which is the introduction of the thesis, the thesis comprises five chapters that are organized as follows:

Chapter 2 introduces the dynamic modeling, the system description, and optimal DG allocations for the case study. Also, this chapter introduces the load flow calculations for the case study to validate the results of the optimal DG allocations for the IEEE 33-bus system.

Chapter 3 presents a description of the proposed framework for load shedding algorithm. The rest of this chapter presents a full example to illustrate the intentional islanding process.

Chapter 4 introduces the simulation results for the transition moment from the normal grid-connected mode to island mode. This chapter introduces the results of the load shedding required to form islands and island combinations. The island configuration is used to study the transition process to island operation with some constrains such as maximum DGs penetration level and maximum percentage shed loads.

Chapter 5 presents the small signal stability analysis for the islands and island combinations. Also, this chapter compares the minimum damping factors of eigenvalues for all islands and island combinations.

Chapter 6 gives the conclusions and recommendations for future work that can be carried out related to this thesis.

CHAPTER 2

Investigated Network

This chapter comprises three sections. The first section introduces the system description and optimal DG allocations, while the second section introduces the dynamic modeling for the DGs components. The dynamic models include the models of generators, turbines and excitation system. The third section introduces the load flow calculations for the case study to validate the results of the optimal DG allocations.

2.1 System Description

To further illustrate the method used in this study, a distribution system like IEEE 69-bus system or IEEE 33-bus system is adopted. The system used in this study is the IEEE 33-bus radial distribution system. This system contains 33 buses and 32 loads and is fed from an infinite bus. The single line diagram is shown in Fig 2-1, and the system data are given in **Appendix A.**

It is well known that this standard system is suffering from poor voltage profile and high-power loss, where one of the solutions to these problems is inserting DGs.

2.1.1 IEEE 33-bus load profile curve

Ref. [41] introduced the load profiles for IEEE 33-bus system. The load profile of IEEE 33-bus has been converted to per unit values and is demonstrated in Fig 2-2. The calculations base of the values indicated in this Fig 2-2 is sum of the loads in this system which is 3.7 MW.

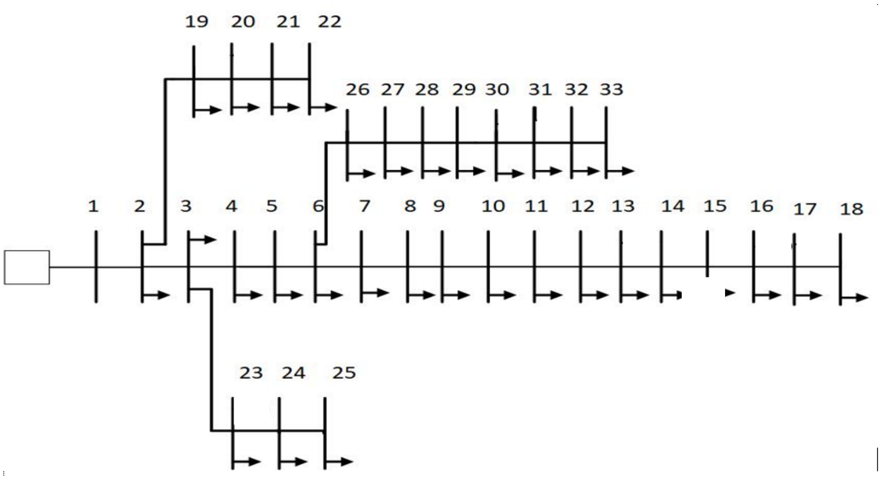


Fig 2-1: IEEE 33-Bus System

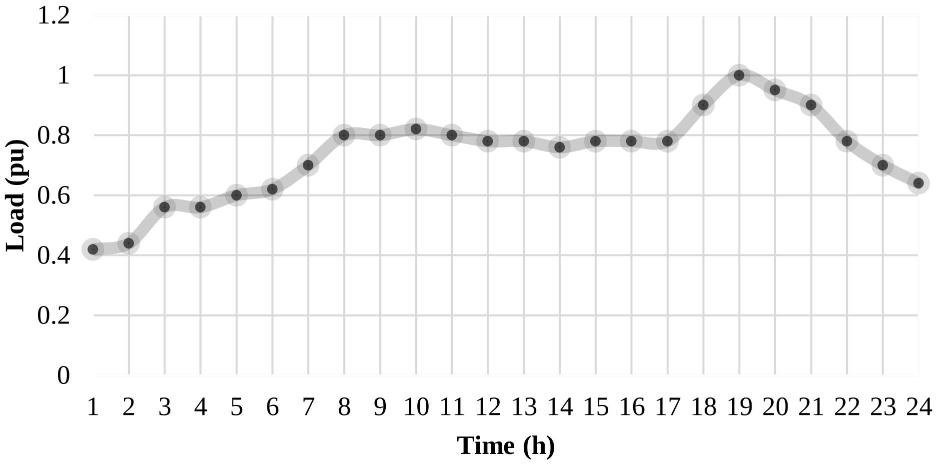


Fig 2-2: Load Profile of IEEE 33-Bus System

2.1.2 Optimal DGs allocations

Inserting DGs could increase the distribution system reliability and security [42]. Most common faults in the distribution systems are temporary faults. Thus, the frequent temporary faults with the existence of DGs could result in instability conditions and, hence, the overall reliability of the system decreases.

From the previous discussion, there is a stability limit for adding more DGs to distribution systems. The stability is not the only limit of inserting more DG units but also the size of conductors, power losses, economics, control strategy…etc. So, the location and size of the DG units must be selected optimally.

The optimal sizing and location of DG units in this study are accomplished through two-steps. In the first step, the optimal location and sizing of DG are identified to reduce power loss and enhance the voltage profile, as detailed in [22, 34, 43]. The Reference [39], recommend five places to add the DG to the IEEE 33-bus system, the locations of the five units is determined by solving An optimization problem with Genatic algorithm technique, the main objectives of this problem are enhance the voltage profile and reduce the power loss. The results recommended installing DG units at Buses 13, 16, 17, 30 and 31.

According to IEEE standards, there are many types of islands [27]. The island type used in this study is the lateral island. In this type, the DGs are required to be distributed over the laterals of the distribution system. Also, the island operation requires adding more DGs to give more flexibility for supplying the isolated loads. Therefore, two more units are inserted at Buses 20 and 23 to enable forming more islands. The selection of these two locations considers the main constraints of total energy supplied by the DG units and enables forming more islands when required. Thus, the total number of DG units is seven with the locations as identified in Table 2-1. The rated power factor for all DG units is 0.8.

The second step of optimal DGs allocation is to determine their sizes. The sizes of DGs in the first step did not consider the penetration level. To complete the second step of optimal DGs allocation, many modifications have to be carried out. The first one is to limit the output power of all DGs to 50% as a maximum penetration level. This limitation has been imposed to realize the practical operation and to reduce the harmful effect of the high penetration level of DG [22, 44].

The limits of the DGs penetration level is introduced due to problems related to distribution system operations. Increasing the penetration level affects the flow of the power, levels of the harmonic and the levels of the voltage [45].

However, the penetration level in the industrial system reaches a high percentage usually (50%:70%) to provide an adequate supply of power to the loads. The rise in voltage level could cause real problems and, so, robust voltage control should be adopted in the system [45]. In this study, a limit of 50% is chosen to provide an adequate supply of power to the loads in the proposed industrial system [40].

Table 2-1: Initial Optimal Allocation of DG Units

Bus	Rating capacity (MVA)	Operating power (MW)
13	0.25	0.1738
16	0.5	0.2914
17	0.25	0.0816
30	0.25	0.1789
31	0.5	0.3888
23	0.5	0.173
20	0.5	0.173

The second modification is the insertion of Static VAR Compensator (SVC) at Bus 29 with capacity of 0.6 Mvar. This modification is required due to the lack of reactive power for the local load connected at Bus 30 in the island mode. The SVC is located at Bus 29 instead of Bus 30 since a DG unit is located at Bus 30. Therefore, it is required to prevent any conflict between the

SVC and the DG when they are located at the same bus. Generally, a restriction is considered to exclude any bus that has a DG from insertion of any other voltage controller device. Regarding the case study, Bus 30 is the most proper one for inserting SVC, but it is excluded, and Bus 29 has the second priority. The final optimal allocation of DG units is demonstrated in Table 2-2 with all DG units having a rated power factor of 0.8.

Table 2-2: Final Optimal Allocation of DG Units

Bus	Rated Active Power (MW)
13	0.169
16	0.338
17	0.169
20	0.338
23	0.338
30	0.169
31	0.338

2.2 Dynamic Models

In this study, the adopted DG type is gas turbine type, so the model of the turbine and excited should selected according to Dg type. in this section introduces the dynamic models of the system elements (generator, turbine and Excitation system).

2.2.1 Generator model

In this thesis, the constant voltage third order sub-transient generator model is used, where the transient parameters for all generators in the system are the same. The detailed models are found in [46]. The model parameters that are used in this study are presented in **Appendix B**.

2.2.2 Turbine model

There are many turbine models that are used in power system investigations. The model employed in this study is GAST model that is appropriate for small-cycle gas turbines. The data and detailed model are found in [47, 48]. The model and parameters that are used in this study are presented in **Appendix C**.

2.2.3 Excitations system model

It is essential to control the generator voltage, especially in the island mode, because the generator feeds the loads directly and separately from the grid. There are three types of excitation systems which are DC excitation, AC excitation and static excitation [49]. The DC excitation system utilizes DC generators as a source of excitation [49]. The AC excitation systems utilize alternators as a source of generator excitation. The AC output of the exciter is rectified by either controlled or diode rectifiers to produce the direct current which is needed for the generator field. The last type is the static excitation systems, where the generator itself is the source of the exciter power, i.e., the generator is self-excited. In this case, the generator must have an auxiliary power source to provide field current and energize the generator at the start of its operation [49].

The DG excitation system could be AC or static types [49, 50]. In this study, the AC type is preferred because this type has fewer auxiliaries than static type. Also, the model is suitable for large-scale simulations as reported by IEEE [49]. So, the model used is in this study is AC4A [51]. The detailed model and parameters are presented in **Appendix D**.

2.3 Load Flow Study

A load flow study is performed for the system in two cases, i.e., with and without DG units. Fig 2-3 indicates the bus voltages in two cases i.e. with DG and without DG the maximum voltage drop in case of the DG is not included reaches to 7% while adding DG decrease this voltage drop to 1.8 %. Table 2-3 summarizes the power losses in the two cases. As shown in Fig 2-3 and Table 2-3, the IEEE 33-bus system is suffering from poor voltage level and high-power loss before adding DG units. The load flow study after adding the DG units confirms the visibility of adding the DG to the distribution system.

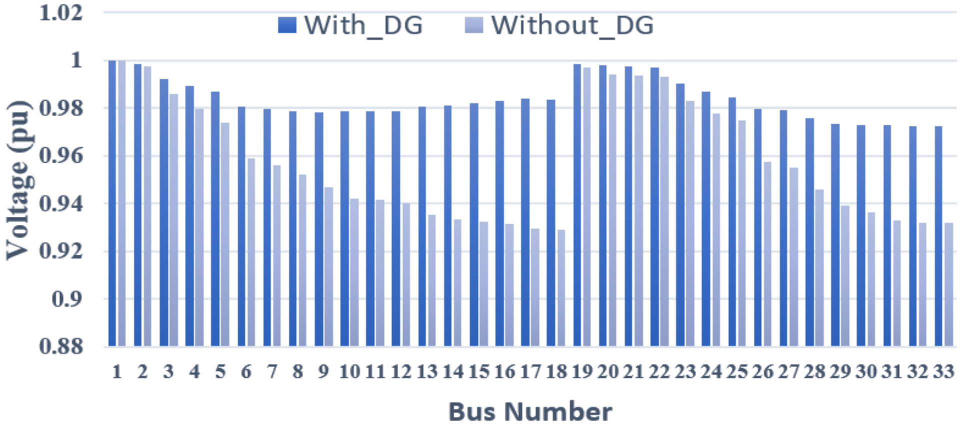


Fig 2-3: Bus Voltages of the Investigated Network

Table 2-3: Power Losses in the Investigated Network

Case	Active power loss		Reactive power loss	
	MW	pu	Mvar	pu
Without DG	0.16249	0.0439	0.108287	0.0293
With DG	0.037528	0.0101	0.02446	0.00661

CHAPTER 3

Proposed Load Shedding Algorithm

To ensure a successful transition to island mode, the corresponding precautions must be satisfied. **Firstly**, the power balance must be satisfied between the loads and DGs. This balance can be achieved via the load shedding mechanism. **Secondly**, there are certain methods to control the voltage and frequency via the exciter Q-E droop and the turbine P-f droop speed (R), respectively. **Thirdly**, the time for load disconnection in the load shedding algorithm must be quick. Other precautions that are not mentioned here could be assumed as found in IEEE 1547.4 [27].

3.1 Procedures and results of the load shedding

Load shedding (LS) means deliberate disconnection of specific loads to maintain supplying power to the other connected loads with acceptable power quality [24, 40]. There are two types of load shedding. The first type is the under-voltage load shedding (UVLS), in which the loads are disconnected to prevent voltage collapse or supply other connected loads in the allowable voltage limit [17, 40]. The second type is the under frequency load shedding (UFLS) that disconnects the loads to prevent the frequency collapse [17, 40].

Regarding the islanding process, load shedding becomes more important for successful transition to stable islanding mode. The procedures used for this study are based on the following principles:

1. Achieving maximum utilization for the DG to increase economic benefits and improve the voltage profile
2. Disconnecting loads according to a predefined priority
3. Achieving fast and quick load shedding since it is accomplished online

Load shedding in the isolated system (island) keeps the frequency within permitted limits with a variation margin of 2% [10]. If the frequency is lower than the previous value, an automated load shedding procedure based on under-frequency relay is initialized to disconnect the loads according to the following criteria:

1. The active and reactive power balance
2. Maximum benefits from all generators in the island
3. Importance of the load

A proposed Load Shedding Algorithm (LSA) is necessary for intentional islanding operation to ensure the load-generation balance. This process should be completed within minimum possible time to perform a successful transition to islanding operation before the protection disconnects the DG. Fig 3-1 demonstrates the load shedding algorithm used for this study. As shown, the proposed mechanism is based on the mentioned principles.

The LSA starts with receiving the control signal to initialize intentional islanding routine, where this signal identifies the island loads and generating units. The island data (generation, loads) are loaded from the system database or estimated from the real system. The data stored in the system database could be measured by PMU units. The second step is to disconnect any load that is higher than the generators capability on the island. The third step is the ranking of the allowable loads in scenarios according to their predefined priority and then, the scenario that achieves maximum utilization of DGs is chosen. This algorithm starts automatically by the control signal after any major contingency for the actual system condition. The system condition is forecasted in real time to get the updated data related to the stability of the system.

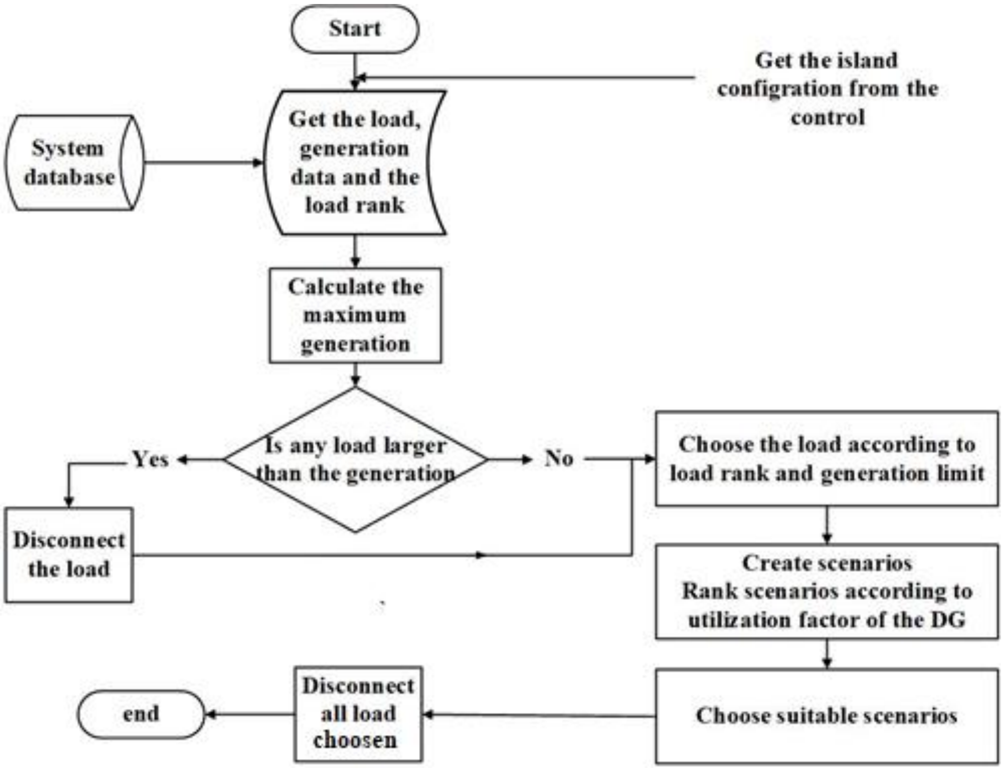


Fig 3-1: Load Shedding Algorithm

3.1.1 LSA Framework

This LSA is developed in MATLAB code and the system condition is stored in a standard access database. This database is extracted using the modeling software (NEPLAN). NEPLAN® is a high-end power system analysis tool for applications in transmission, distribution, generation, industrial, renewable energy systems, Smart Grid application [52]. All the following results are obtained via this MATLAB script that is given in **Appendix E.**

For this study, the load shedding procedure disconnects the loads according to the following defined steps.

1. All loads that are greater than the generator rating will be disconnected.

2. Suitable loads are selected to ensure supplying the maximum number of customers.

An example is detailed to explain the load shedding process for the island (4). The loads and generation in this island are shown in Table 3-1**.**

Table 3-1: Island (4) Loads and Generation

Load data							
Priority	Bus	P (MW)	Q (Mvar)	Priority	Bus	P(MW)	Q (Mvar)
1	16	0.06	0.02	7	12	0.06	0.035
2	17	0.06	0.02	8	11	0.045	0.03
3	13	0.06	0.035	9	10	0.06	0.02
4	14	0.12	0.08	10	9	0.06	0.02
5	15	0.06	0.01	11	8	0.2	0.1
6	18	0.09	0.04	12	7	0.2	0.1
Generator data							
Bus	S (MVA)	PF	Bus	S (MVA)	PF		
13	0.25	0.8	17	0.25	0.8		
16	0.5	0.8		-			

Island (4) active load power is equal to 1.075 MW, which cannot be supplied by active power generation, i.e., 0.8 MW and hence, load shedding is required. Table 3-1 indicates the load priority, which is developed according to the assumed importance of loads. The highest priority, as shown in Table 3-2**,** is assumed to be for loads connected to Bus 16 then, load center 17 and so on. The algorithm will choose scenario two for 0.8 MW generation power because the loads connected to Bus 8 is more important than load center at Bus 7.

Table 3-2: Load Shedding Scenarios

Scenario number	Load bus numbers for scenarios										Summation of loads
1	16	17	13	14	15	18	12	11	10	9	0.675
2	16	17	13	14	15	18	12	11	8	-	0.7551
3	16	17	13	14	15	18	12	11	7	-	0.7551

3.1.2 Case Study

This section introduces the dynamic analysis for four islands to illustrate the working principles of the LSA. First of all, the type which had been selected for island is lateral island [27] that is shown in Fig 3-2 with four possible islands. The objective is to introduce the concept of intentional islanding. All islands are detailed in the following sections. The program used in this study is NEPLAN software package.

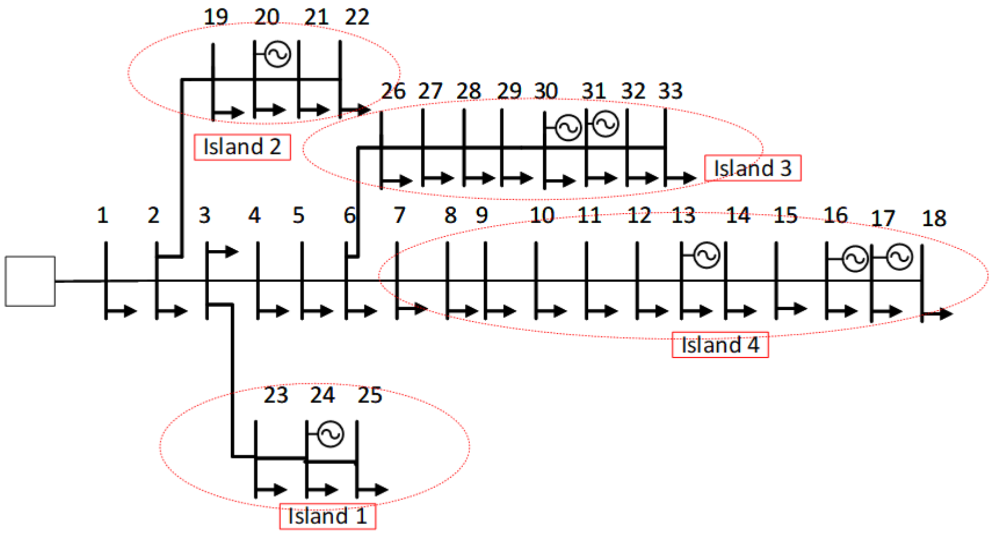


Fig 3-2: The Case Study of Four Lateral Islands

3.1.2.1 Simulation results of Island (1)

The new island will be established intentionally by the network operator or unintentionally using protective relaying. It is formed by the outage of the line connecting Bus 3 with Bus 23. The line disconnection occurs after 2.0 s from the beginning of the simulation time. Island (1) contains Buses 23, 24 and 25. The data of island 1 are shown in Table 3-3. The first column of the

Table contains the bus number and the loads are ranked by the defined priority that is the load at bus 23 is more important than the load at bus 24 and so on.

Table 3-3: Data of Island (1)

Bus	Load	Generator rating
23	0.09 MW, 0.05 Mvar	-
24	0.42 MW, 0.2 Mvar	0.5 MVA at 0.8 PF lag.
25	0.42 MW, 0.2 Mvar	-

Fig 3-3, Fig 3-4, Fig 3-5 and Fig 3-6 show the voltage, frequency, active power, and reactive power, respectively in two cases, i.e., with and without load shedding. The loads will be disconnected after 0.1 s of line trip to have successful intentional islanding. From Table 3-3, the load shedding algorithm should be applied to disconnect the loads at Bus 24 and Bus 25. If this load is not disconnected, the generator cannot support the voltage because of the reactive power shortage as shown in Fig 3-6**.**

The generator will produce more reactive power to support the voltage level but if the loads are not disconnected at a suitable time, the voltage will collapse as shown in Fig 3-3**.** The power imbalance in this island will cause the generator to trip by under frequency relay as shown in Fig 3-4 if the loads are not disconnected at a suitable time**.**

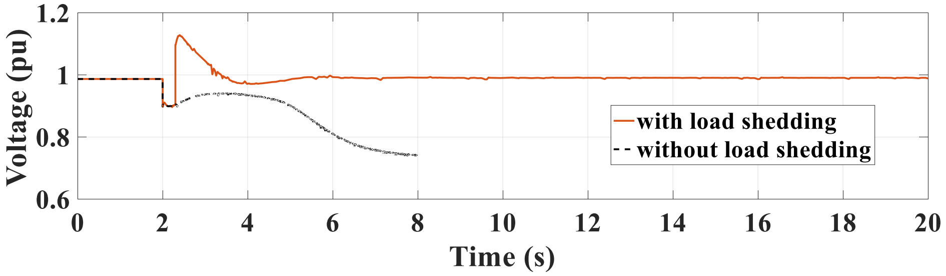


Fig 3-3: Output Voltage of the Generator at Bus 24

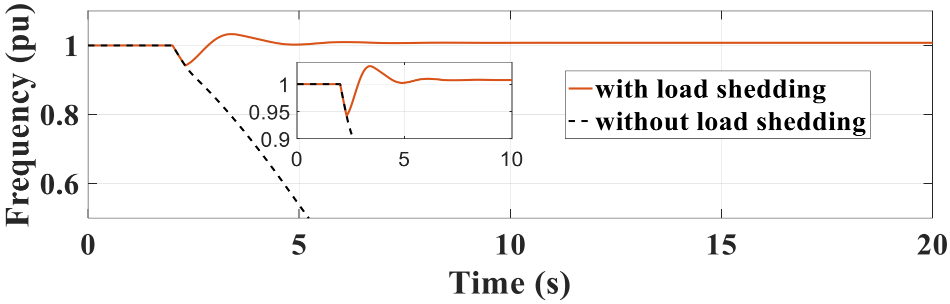


Fig 3-4: Frequency of the Generator at Bus 24

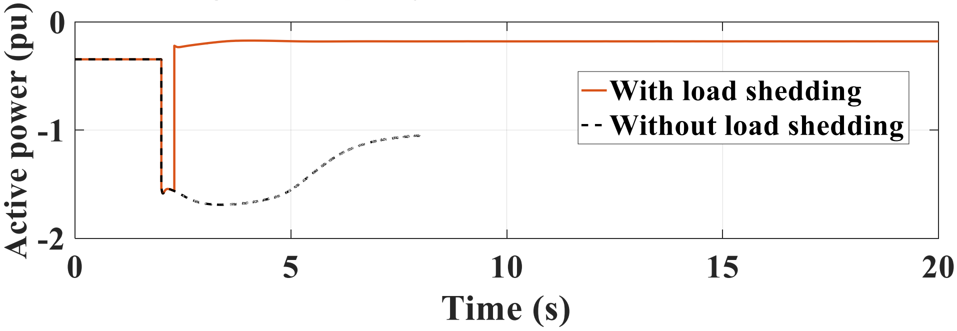


Fig 3-5: Output Active Power of the Generator at Bus 24

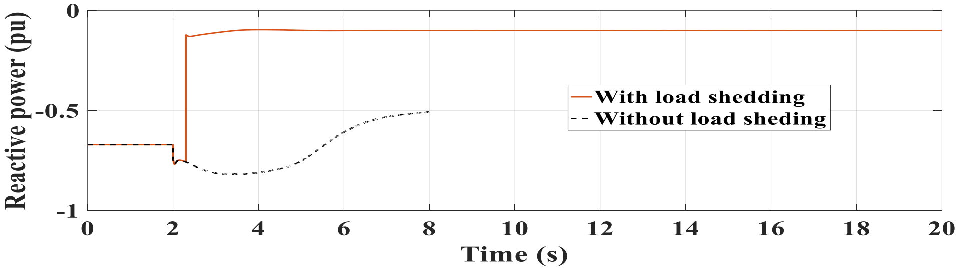


Fig 3-6: Output Reactive Power of the Generator at Bus 24

3.1.2.2 Simulation results of Island (2)

Similar to the case of Island (1), Table 3-4 summarizes generators and loads information and the priority of the loads. In this island, the summation of loads is less than the generator capability. Thus, the load shedding algorithm will not be activated.

Table 3-4: Data of Island (2)

Bus	Load	Generator rating
19	0.09 MW, 0.04 Mvar	-
20	0.09 MW, 0.04 Mvar	0.5 MVA at 0.8 PF lag
21	0.09 MW, 0.04 Mvar	-
22	0.09 MW, 0.04 Mvar	-

As mentioned earlier, **droop control** is a method to control the synchronous generator frequency. The generator will be isolated from the main grid and the load frequency control will let the frequency to decrease to meet the load demand. The governor of the generator at Bus 20 must increase the output power by 0.382 pu to meet the load demand. This causes the generator to operate at a frequency of 0.983 pu when the speed droop **(R)** of the turbine is 0.047. The speed droop **(R)** of the governor needs to be changed to make the generator operate at a higher frequency. When the speed droop is modified to 0.02, the generator frequency is increased to 0.993 pu. The second speed droop is chosen to ensure a good operation with minimum voltage oscillations. So, Fig 3-7 indicate the two-speed droops of the governor.

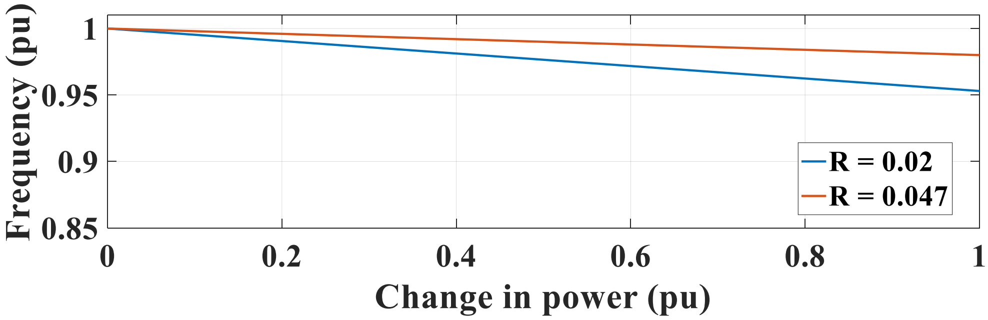


Fig 3-7: Speed Droops of Generators

Fig 3-8, Fig 3-9 and Fig 3-10 exemplify the behavior in the transient stage. As shown in Fig 3-9**,** the frequency decreases to 0.982 pu because the turbine governor has a speed droop controller. This frequency is within the acceptable range and the protection will not be activated to disconnect the generator at Bus 20. But to improve the frequency level to be closer to its nominal value, the turbine speed droop is modified to modify the frequency to be 0.993 pu.

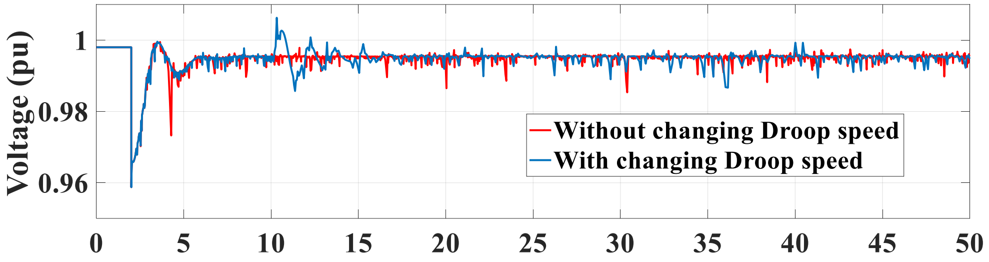


Fig 3-8: Output Voltage of the Generator at Bus 20

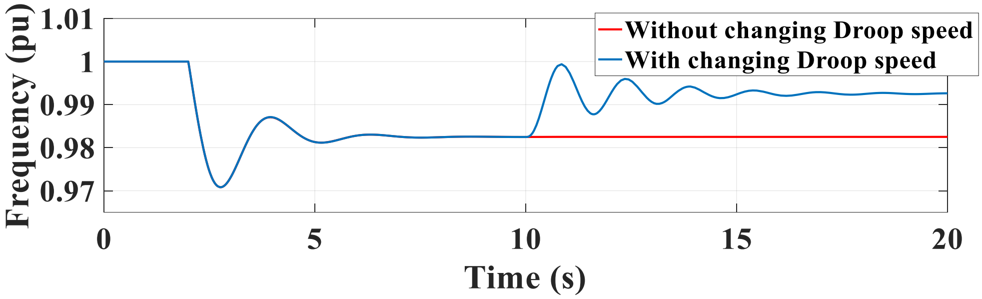


Fig 3-9: Frequency of the Generator at Bus 20

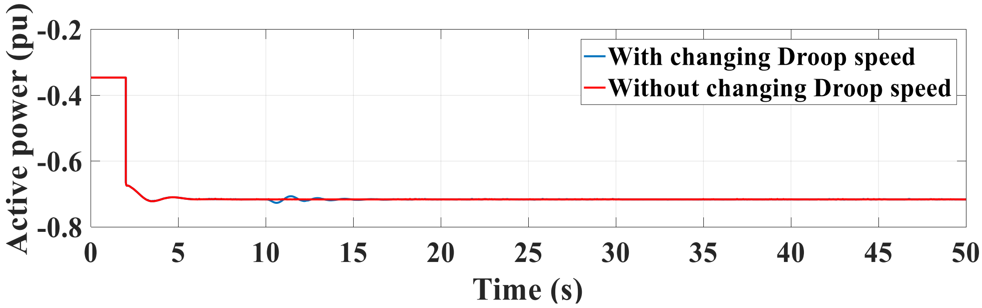


Fig 3-10: Output Active Power of the Generator at Bus 20

3.1.2.3 Simulation results of Island (3)

Table 3-5 shows the load and generation in Island (3) as well as the loads priority. As shown in the table, the load at bus 30 is more important than the load at bus 31 and so on. Similar to Island (1), the generation is less than loads, which causes frequency decrease. To prevent this problem, the loads at Buses 26, 27 and 30 will be disconnected. The loads are disconnected based on the working principles of the LSA.

Table 3-5: Data of Island (3)

Bus	Load	Generator rating
30	0.2 MW, 0.6 Mvar	0.25 MVA at 0.8 PF lag
31	0.15 MW, 0.07 Mvar	0.5 MVA at 0.8 PF lag
32	0.21 MW, 0.1 Mvar	-
29	0.12 MW, 0.07 Mvar	-
33	0.06 MW, 0.04 Mvar	-
28	0.06 MW, 0.02 Mvar	-
27	0.06 MW, 0.025 Mvar	-
26	0.06 MW, 0.025 Mvar	-

The loads at buses 27 and 26 had been disconnected because they have the lowest priority among others loads in the island, while the load at bus 30 is disconnected to achieve one of the LSA principles which is achieving the maximum utilization for the local distributed generations units.

Fig 3-11, Fig 3-12 and Fig 3-13 demonstrate the behavior in the islanding moment. For this island, the load will be disconnected after 0.6 s from the transition moment. Fig 3-11 shows the frequency with and without load shedding. The load shedding algorithm disconnects the loads after 0.6 s when the frequency decreases to 0.98 pu. After the load shedding, the generator frequency returns to its permitted value. The change in speed droop is no longer needed for this situation. Fig 3-12 shows the output active and reactive power of the generators.

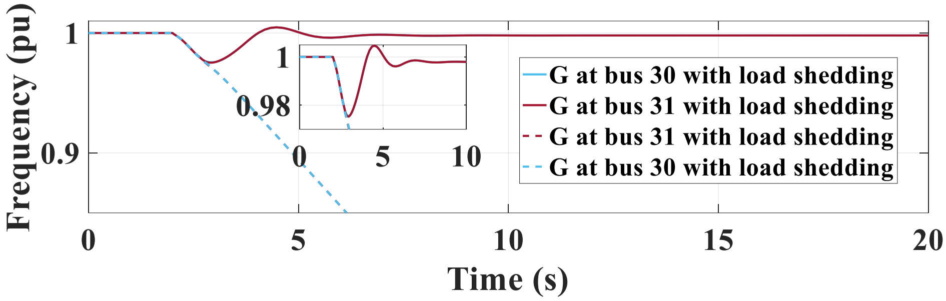


Fig 3-11: Frequency of the Generators at Buses 30 and 31

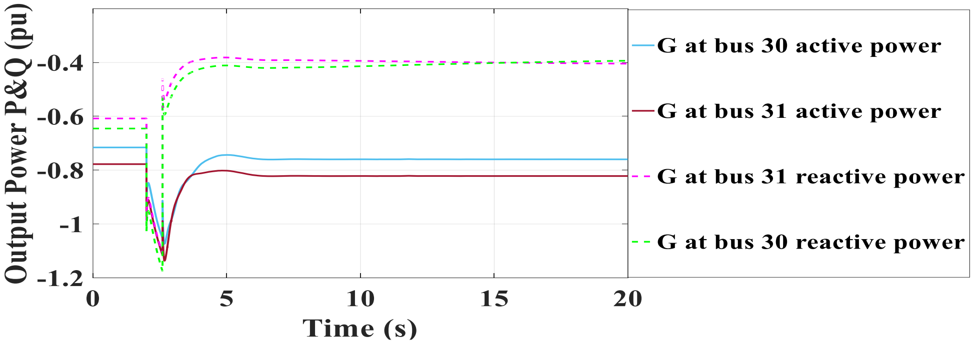


Fig 3-12: Output Power of the Generators at Buses 30 and 31

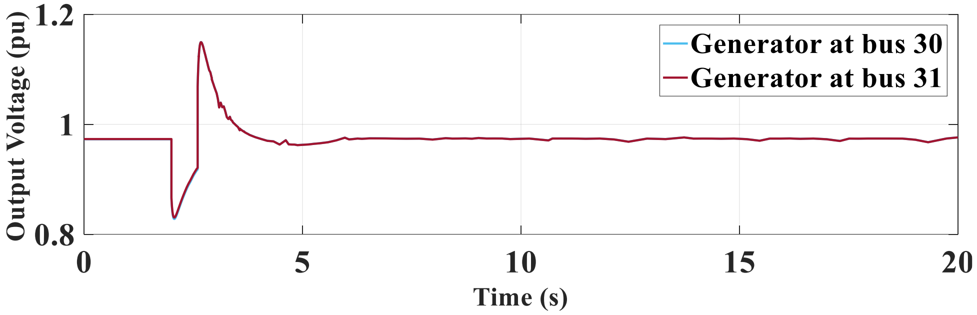


Fig 3-13: Output Voltage of the Generators at Buses 30 and 31

3.1.2.4 Simulation results of Island (4)

Table 3-6 shows the data of Island (4). This island contains three generators, dissimilar to other islands. Therefore, this island could exhibit stability problems related to the angle stability between the generators in the island. Loads of island (4) are larger than the allowable generation. Load centers at Buses 9, 7 and 10 will be disconnected according to the load shedding algorithm after 0.16 s. Fig 3-14 illustrates the time response of the generators frequencies for Island (4).

Table 3-6: Data of Island (4)

Bus	Load	Generator rating
16	0.06MW, 0.02 Mvar	0.5 MVA at 0.8 PF lag
17	0.06 MW, 0.02 Mvar	0.25 MVA at 0.8 PF lag
13	0.06 MW, 0.035 Mvar	0.25 MVA at 0.8 PF lag
14	0.12 MW, 0.08 Mvar	-
15	0.06 MW, 0.01 Mvar	-
18	0.09 MW, 0.04 Mvar	-
12	0.06 MW, 0.035 Mvar	-
11	0.045 MW, 0.03 Mvar	-
10	0.06 MW, 0.02 Mvar	-
9	0.06 MW, 0.02 Mvar	-
8	0.2 MW, 0.1 Mvar	-
7	0.2 MW, 0.1 Mvar	-

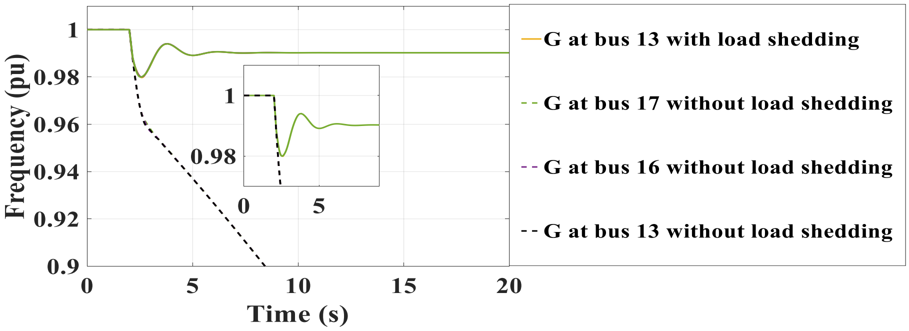


Fig 3-14: Frequency of the Generators at Buses 13, 16 and 17

Fig 3-15 shows the rotor angle difference between the generators in the island. This graph indicates that the system in the island will be stable after creating this island.

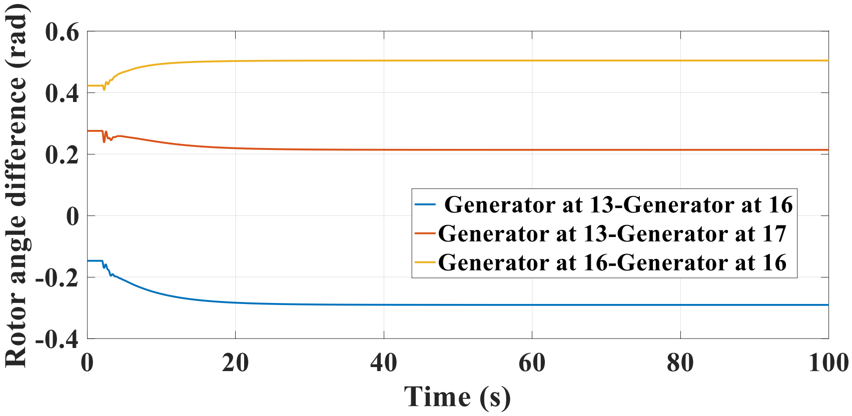


Fig 3-15: Rotor-angle Difference between the Generators in Island (4)

3.2 Island control tools

The system is controlled via two layers of control, i.e., centralized control and distributed control systems [32]. Each control type has its role in the transition moment. The role of the centralized control system is to initiate the intentional islanding routine according to system stability studies. The role of the disturbed control system is to control new island operation of the isolated system [32].

The island is subjected to disturbances of increasing or decreasing the local loads. The existence of control functions which regulate the output power of the DG is an important issue. This regulation is performed via the distributed control system (DCS).

The Automatic Voltage Regulator (AVR) is used to maintain the generator output voltage fixed around the operating value and within permitted limit. However, it is essential to ensure that the load reactive power does not exceed the rated reactive power of generators.

To control the speed of the generator, the governor can operate in many modes such as droop control mode for power-sharing and isochrones mode for the standalone applications [53]. The droop control is mainly used when the generator is connected to the grid for active power-sharing.

The speed droop **(R)** is a relation between the change in frequency and the change in generator output power, and it is regulated by the load frequency control system to maintain the generator frequency at its original value.

When the generator operates in island mode, the isochrones mode forces the output frequency of the generator to be fixed. Hence, it is impossible to achieve load sharing if all generators in the system are controlled by this type of control. However, it is useful for standalone applications since there is no need for load sharing.

3.3 Summary

This chapter introduced LSA to enhance the intentional islanding operations. It introduced also full dynamic analysis for four islands with highlighting the control philosophy of the voltage and frequency.

CHAPTER 4

Results of Transient Behaviour

This chapter introduces the dynamic analysis for the transition moment from normal mode (grid-connected mode) to isolated mode (island mode). The chapter illustrates the island configuration for the case study and the load shedding results for all possible island and island combinations. Finally, the results of the dynamic behavior of four islands are introduced.

4.1 Island Configuration

Choosing the island configurations is a challenging problem. Many researchers propose new methodologies to choose the island configurations such as the research introduced in [35], which introduced a probabilistic approach to increase the probability of proper operation of the new islands.

In this study, the configuration is selected according to many practical conditions. These conditions include the system topology, maximum DGs penetration level, and allowable LS limit. The island configuration is chosen based on two factors: the allocation of the DGs and the system **load profile** during the day [41]. The load profile is illustrated in Fig 2-2. The average load is 0.73 pu.

To realize practical and reasonable operation for the new islands, a limit must be imposed for the disconnected loads. For this study, this limit is assumed to be 30% in any new island for the average load [35]. The total capacity of DGs is not exceeding 50% of the total demand in this system[54], [55]. This configuration is indicated in Fig 4-1.

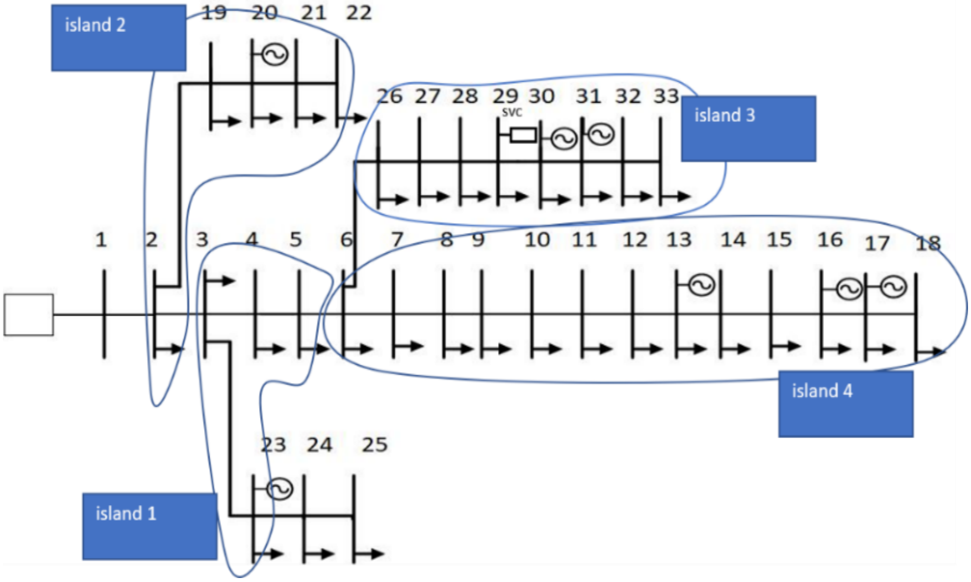
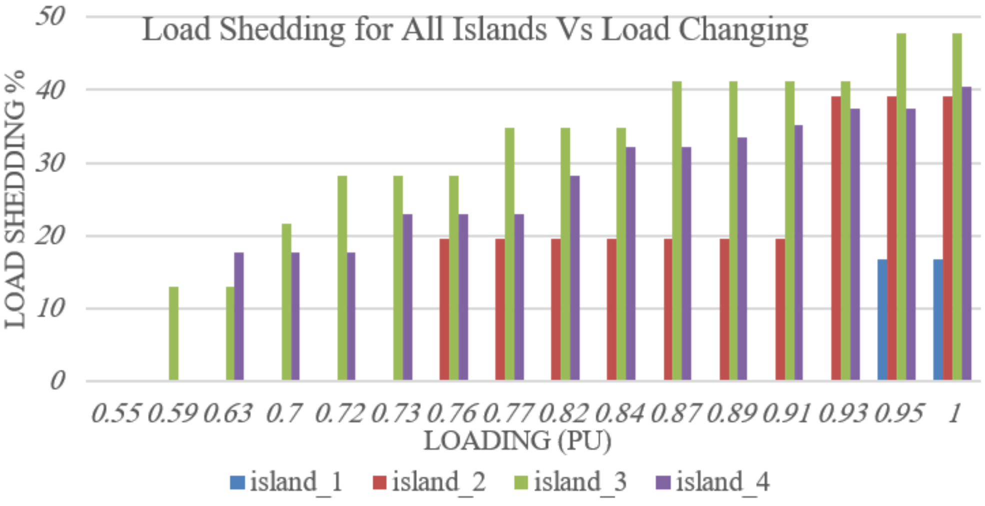


Fig 4-1: IEEE 33-bus Island Configuration

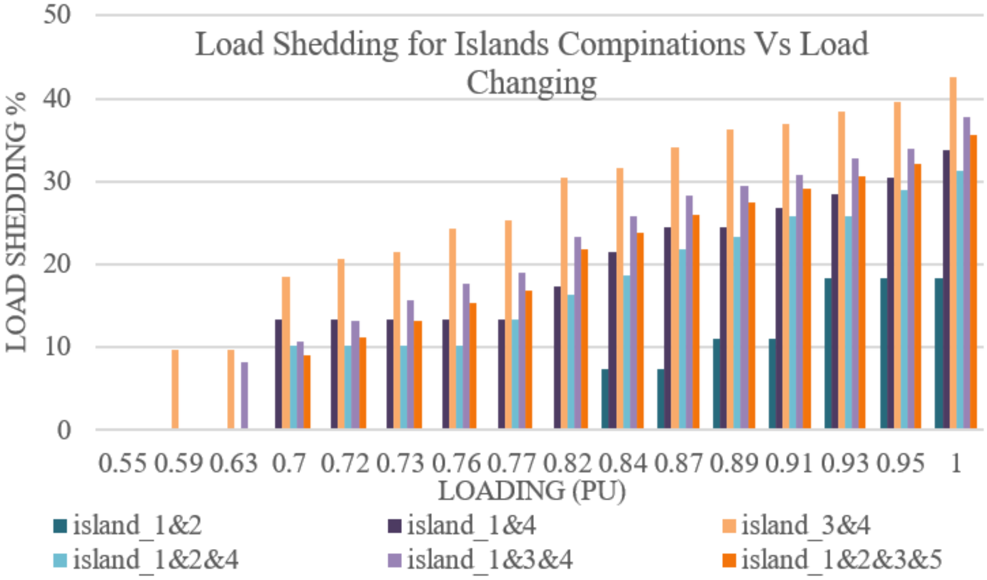
4.2 LSA Result for Islands and Island Combinations

The percentage load shedding is calculated every hour according to the load profile demonstrated in Fig 2-2. Some of these results are identical. For simplification, the cases are clustered into 16 clusters. One case is selected from every cluster to represent the cluster. These 16 cases are demonstrated in Fig 4-2 for islands and islands combinations.

As shown in Fig 4-2, the percentages load shedding for combined islands are less than the separated islands. Obviously, the reliability of the system is increased by combining the islands.



(a)



(b)

Fig 4-2: Load Shedding of Islands and Combinations Versus Load Changes

4.3 Time and loading limitations for successful transition

4.3.1 Time limitations for successful transition

The maximum allowable time to disconnect the loads in any island for the case study in **chapter 3** is determined based on the stability limit for each island. So, this time is not the same for different islands. Generally, the loads have to be disconnected as fast as possible to prevent any stability problems. In the island configuration, the timing to execute the LSA is determined based on the time lag for the circuit breaker, algorithm execution time and communication lag time [56]. This time is 15 cycles that is equivalent to 0.3 s and thus, all shed loads have to be disconnected within 0.3 s.

4.3.2 Loading limitations for successful transition

In this section, all loading conditions for each island will be demonstrated. The average loading condition will be considered at the last part of this section.

Table 4-1 indicates the details of the DGs in each island, where the third column in this table indicates the maximum output of the DG(s) for each island. Table 4-2, Table 4-3, Table 4-4 and Table 4-5 indicate the detailed loading and the percentage load shedding for island (1), island (2), island (3) and island (4), respectively. The first column in these tables represents the 16 cases mentioned in **section 4.2**, while the second column (P_{isalnd}) is the summation of all loads in each island, the third column ($P_{remainning}$) is the summation of the loads that remain in service after applying the LSA, and finally "LS" represent the percentage load shedding for each island. The "DG loading (%)" is the ratio between the remaining loads and DG capacity for each island.

Table 4-1: The Details of the DGs in Each Island

Island	Number of the DG units	Max Output of DGs (MW)
Island 1	1	0.33776
Island 2	1	0.33776
Island 3	2 + SVC	0.507
Island 4	3	0.676

Table 4-2: The Detailed Load and DG loading for Island (1)

Percentage Loading	Load			DG loading (%)
	$P_{island}\ (MW)$	$P_{remainning}\ (MW)$	LS (%)	
55	0.198	0.198	0	58.62
59	0.2124	0.2124	0	62.88
63	0.2268	0.2268	0	67.15
70	0.252	0.252	0	74.61
72	0.2592	0.2592	0	76.74
73	0.2628	0.2628	0	77.81
76	0.2736	0.2736	0	81.00
77	0.2772	0.2772	0	82.07
82	0.2952	0.2952	0	87.40
84	0.3024	0.3024	0	89.53
87	0.3132	0.3132	0	92.73
89	0.3204	0.3204	0	94.86
91	0.3276	0.3276	0	96.99
93	0.3348	0.3348	0	99.12
95	0.342	0.285	16.667	84.38
100	0.36	0.3	16.667	88.82

Table 4-3: The Detailed Load and DG loading for Island (2)

Percentage Loading	Load			DG loading (%)
	$P_{island}\ (MW)$	$P_{remainning}\ (MW)$	LS %	
55	0.253	0.253	0	74.91
59	0.2714	0.2714	0	80.35
63	0.2898	0.2898	0	85.80
70	0.322	0.322	0	95.33
72	0.3312	0.3312	0	98.06
73	0.3358	0.3358	0	99.42
76	0.3496	0.2812	19.56	83.25
77	0.3542	0.2849	19.56	84.35
82	0.3772	0.3034	19.56	89.83
84	0.3864	0.3108	19.56	92.02
87	0.4002	0.3219	19.56	95.30
89	0.4094	0.3293	19.56	97.50
91	0.4186	0.3367	19.56	99.69
93	0.4278	0.2604	39.13	77.10
95	0.437	0.266	39.13	78.75
100	0.46	0.28	39.13	82.90

Table 4-4: The Detailed Load and DG loading for Island (3)

Percentage loading	Load			DG loading (%)
	$P_{island}\ (MW)$	$P_{remainning}\ (MW)$	LS %	
55	0.51	0.506	0	99.80
59	0.54	0.472	13.043	93.10
63	0.58	0.504	13.043	99.41
70	0.64	0.476	26.087	93.89
72	0.66	0.490	26.087	96.65
73	0.67	0.496	26.087	97.83
76	0.7	0.494	29.348	97.44
77	0.7	0.501	29.348	98.82
82	0.75	0.484	35.870	95.46
84	0.77	0.496	35.870	97.83
87	0.80	0.487	39.130	96.06
89	0.82	0.498	39.130	98.22
91	0.88	0.482	42.391	95.07
93	0.86	0.493	42.391	97.24
95	0.87	0.504	42.391	99.41
100	0.92	0.470	48.913	92.70

Table 4-5: The Detailed Load and DG loading for Island (4)

Percentage Loading	Load			DG loading (%)
	P_{island} (MW)	$P_{remainning}$ (MW)	LS %	
55	0.62	0.62	0	92.410
59	0.67	0.67	0	99.131
63	0.72	0.59	17.62	87.199
70	0.79	0.65	17.62	96.888
72	0.82	0.67	17.62	99.657
73	0.83	0.64	22.91	94.557
76	0.86	0.67	22.91	98.443
77	0.87	0.67	22.91	99.738
82	0.93	0.67	28.19	98.931
84	0.95	0.65	32.16	95.748
87	0.99	0.67	32.16	99.168
89	1.01	0.67	33.48	99.472
91	1.03	0.67	35.24	99.013
93	1.06	0.66	37.44	97.747
95	1.08	0.67	37.44	99.849
100	1.14	0.68	40.53	99.923

For all islands, Table 4-6 summarizes the load shedding status under the average loading conditions for each island. The dynamic behavior for each island is investigated under the average loading conditions. The following sections introduce the dynamic behavior for each island in the IEEE 33-bus system.

Table 4-6: Load Shedding Details under Average Loading for Each Island

Island	Percentage load shedding (%)	Disconnected loads
Island 1	0	-
Island 2	0	-
Island 3	26.1	Bus 33, 28, 27, 26
Island 4	22.9	Bus 7, 9

4.4 The dynamic behavior of Island (1)

Generally, the loads will be disconnected, if required, after 0.3 s of the control signal to form the island as mentioned earlier in the thesis. To form Island (1), the following lines must be disconnected:

1. the line located between Bus 2 and Bus 3
2. the line located between Bus 5 and Bus 6
3. the line located between Bus 23 and Bus 24

Table 4-7 summarizes the loading and rating of DGs for this island that contains 4 loads with one DG unit. According to the load shedding algorithm, no load will be disconnected from this island. Fig 4-3 shows the variations of voltage, frequency, active power and reactive power for the transition moment of DG for Island (1). The voltage and frequency of the island will return to normal values after the transition moment. The active and reactive powers are changed also to meet the new loading conditions as shown in Fig 4-3.

Table 4-7: Data of Island (1)

Bus number	Load	Generator rating
23	0.09 MW, 0.05 Mvar	0.422 MVA
3	0.09 MW, 0.04 Mvar	-
4	0.12 MW, 0.08 Mvar	-
5	0.06 MW, 0.03 Mvar	-

Fig 4-3-A demonstrates the voltage of the DG at bus 23. This figure indicates the returning of the output voltage to its nominal value to guarantee high power quality of the supplied power. Fig 4-3-B indicates the output active power of the DG at bus 23 in translation moment. The output power of the DG is changed to meet the new demand of the island, where the active power was increased from 0.4 pu in grid connected mode to 0.6 pu in island mode. The transition between these stats causes tough dynamic as indicated in Fig 4-3-B.

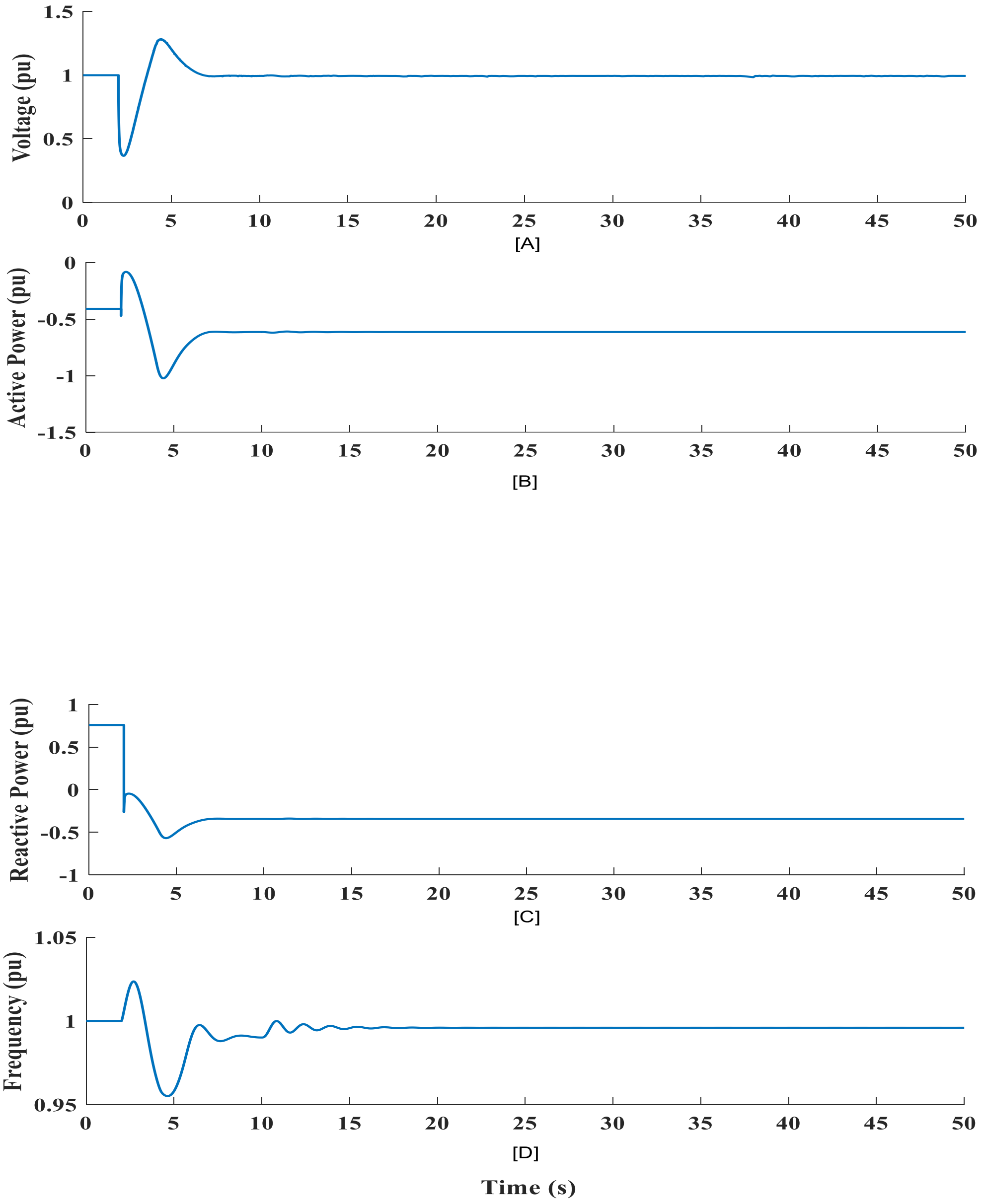


Fig 4-3: The Output Response of the Generator at Bus 23

The reactive power demand in this island has been changed from 0.75 pu to -0.34 pu (negative sign means that the reactive power is generated) to meet the new requirement of the loads as shown in Fig 4-3-C. Finally, Fig 4-3-D indicates the frequency response of the DG in island 1.

In this island, the frequency level has to be modified to enhance the power quality since it will take a value around 0.99 pu. Changing the frequency can be achieved via changing the speed droop (R) as shown in Fig 3-7. According to the situation of the entire system, the distributed control system will modify **the speed droop** (R) of the governor from 0.047 to 0.02 to ensure better operation especially for the frequency that has to be maintained near its nominal value, i.e., 1.0 pu as shown in Fig 4-3 at t=10 s. The 0.02 value is realized via trial and error, where decreasing this value below 0.02 will cause high oscillations.

4.5 The dynamic behaviour of Island (2)

As explained with island (1), Table 4-8 summarizes the loading and rating of DGs for Island (2). The line located between Buses 1 and 2 will be disconnected in addition to disconnecting the line located between Buses 2 and 3.

Table 4-8: Data of Island (2)

Bus number	Load	Generator rating
19	0.09 MW, 0.04 Mvar	-
20	0.09 MW, 0.04 Mvar	0.422 MVA
21	0.09 MW, 0.04 Mvar	-
22	0.09 MW, 0.04 Mvar	-
2	0.1 MW, 0.06 Mvar	-

Table 4-3 indicates the loading condition for island 2. As shown in this table, the percentage load shedding under average loading is 0% meaning that no load will be disconnected. Fig 4-4 indicates the response of the DG connected at bus 20.

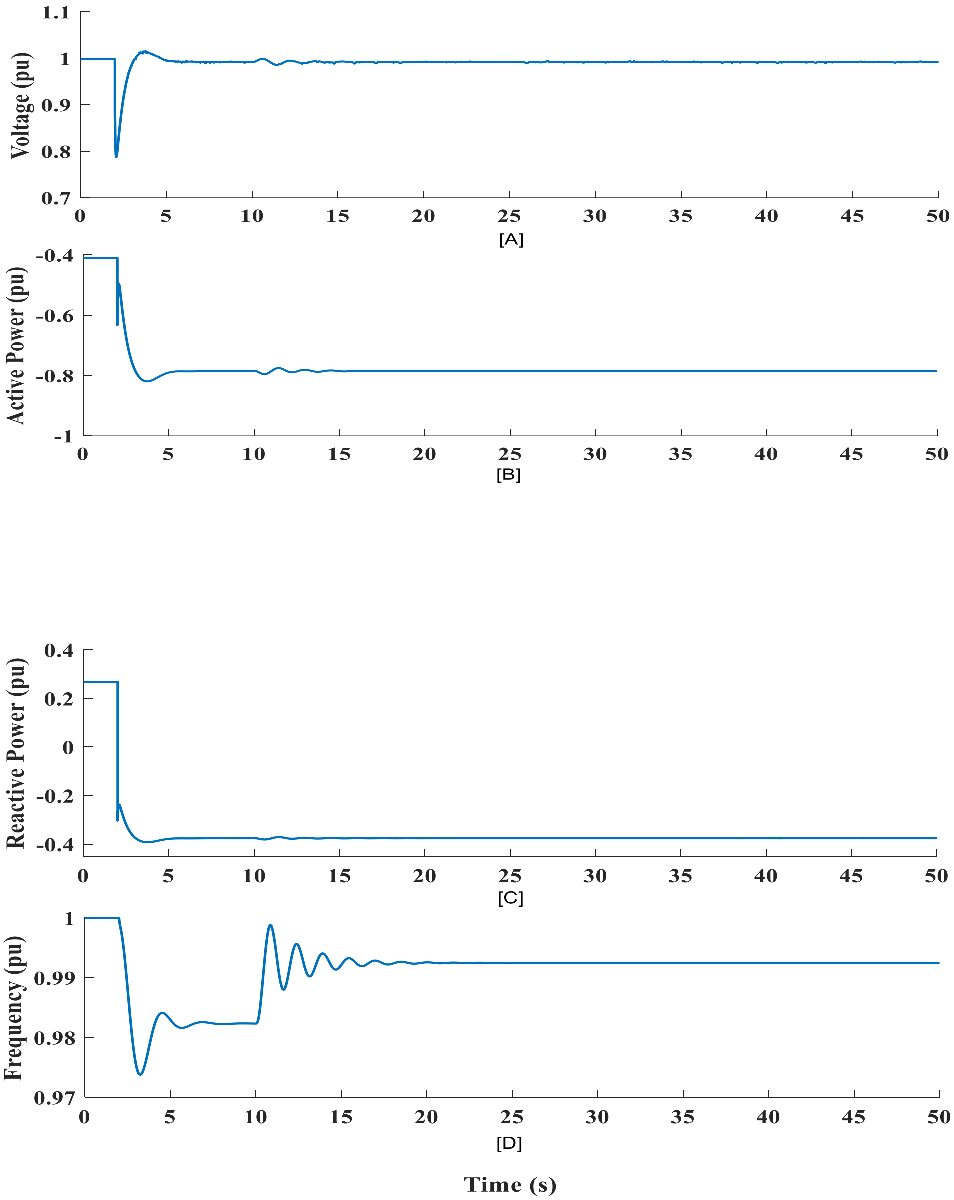


Fig 4-4: The Output Response of the Generator at Bus 20

This response shows a successful tarnation to island mode. This transition causes fluctuations in the voltage as indicates in Fig 4-4-A, while Fig 4-4-B indicates the active power response of the DG. Figure 4-4-C indicates the output reactive power of the DG connected at bus 20. The output reactive power change from 0.27 pu in grid connected mode to -0.38 pu in island mode to meet the new load requirements.

The output active power changes from -0.41 pu in grid connected mode to -0.78 pu in island mode, which causes fluctuations in the frequency as shown in the figure Fig 4-4-D.

Similar to the previous island, the turbine droop speed needs to be modified to increase the frequency level. The droop speed will be changed after 10 s as shown in Fig 4-4-D causing a small overshoot in voltage and the output power as shown.

4.6 The dynamic behavior of Island (3)

Island (3) will be formed by disconnecting the line between Bus 6 and Bus 26. Table 4-9 demonstrates the data of Island (3).

Table 4-9: Data of Island (3)

Bus number	Load	Generator rating
30	0.2 MW, 0.6 Mvar	0.211.MVA
31	0.15 MW, 0.07 Mvar	0.422MVA
32	0.21 MW, 0.1 Mvar	-
29	0.12 MW, 0.07 Mvar	SVC
33	0.06 MW, 0.04 Mvar	-
28	0.06 MW, 0.02 Mvar	-
27	0.06 MW, 0.025 Mvar	-
26	0.06 MW, 0.025 Mvar	-

For average loading conditions of island 3, loads at buses 33, 28, 27 and 26 will be disconnected according to LSA. Fig 4-5 and Fig 4-6 illustrate the response of the local DGs at buss 30 and 31 in three cases: without applying the LSA (without disconnecting any loads), with disconnecting the load at bus 33 only (6.5 % load shedding) and with disconnecting loads identified by LSA.

Without disconnecting any loads, the frequency of DGs in the Island 3 will be decreased until disconnected by the protection system as shown in Fig 4-5-B and Fig 4-6-B. With disconnecting the load at bus 33 only, the DGs in the island 3 will be overloaded as shown in Fig 4-5-C and Fig 4-6-C and the frequency will decrease below the allowable limits as shown in Fig 4-5-B and Fig 4-6-B. In this case, the protective relaying will disconnect the DGs to prevent any damage.

When the LSA is applied, the loads at Buses 33, 28, 27 and 26 will be disconnected to supply the remaining loads under acceptable power quality (proper frequency and voltage) as shown in Fig 4-5 and Fig 4-6 .

In case of applying the LSA, the output active power of the generator at Bus 30 is modified from -0.92 pu in island mode to -0.81 pu in grid connected mode as shown in Fig 4-5-C, while the active power of the generator at bus 31 is modified from -0.85 pu in grid connected mode to -0.73 pu in island mode, as shown in Fig 4-6-C, to meet the new load requirements. The transition in the active power will cause fluctuations in the frequency as shown in Fig 4-5-B and Fig 4-6-B.

For the reactive power, the output reactive power of the DG at bus 30 is modified from 0.39 pu in grid connected mode to 0 pu in island mode as shown in Fig 4-5-D and the reactive power for the DG at bus 31 is modified from 0.53 pu to -0.13 pu as shown in Fig 4-6-D to meet the new load requirements. This causes fluctuations in the voltage as shown in Fig 4-5-A and Fig 4-6-A.

As a conclusion, the LSA guarantee a successful transition to island mode and ensure high power guilty operations.

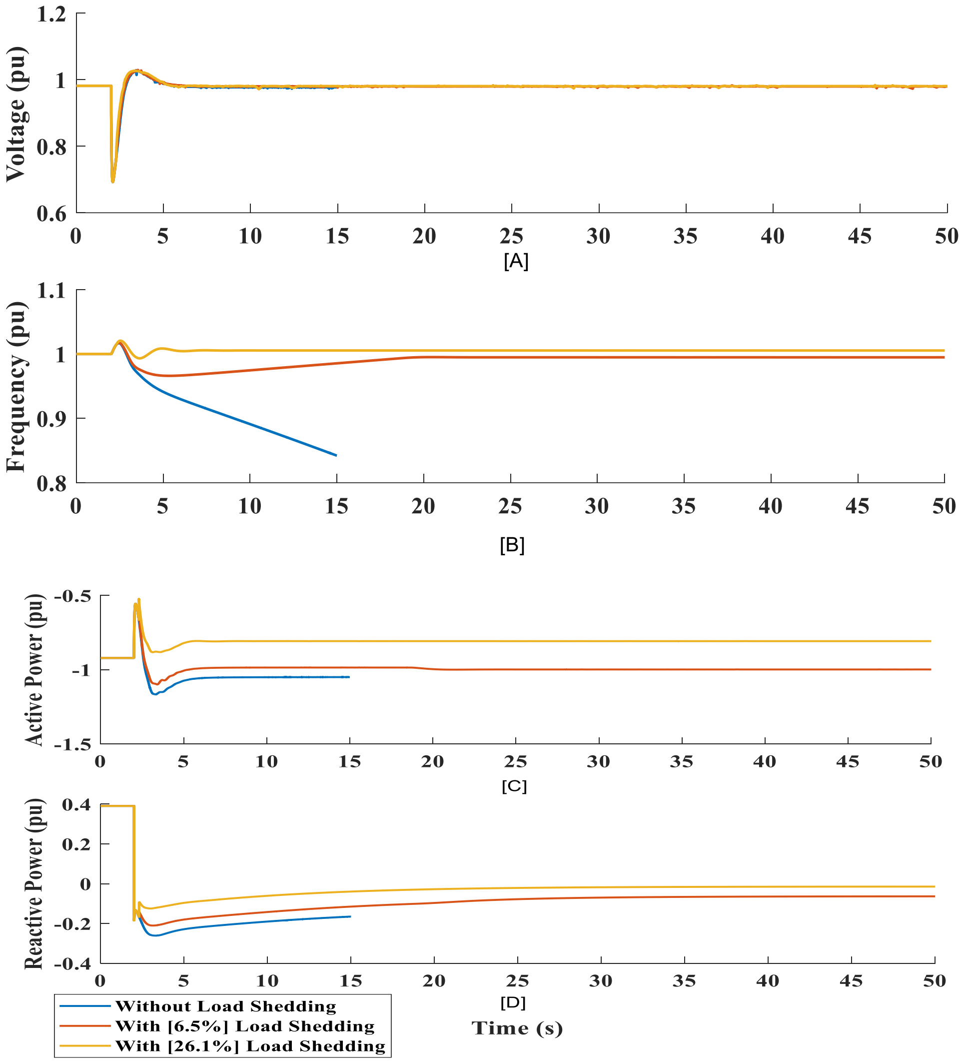


Fig 4-5: The Output Response of the Generator at Bus 30

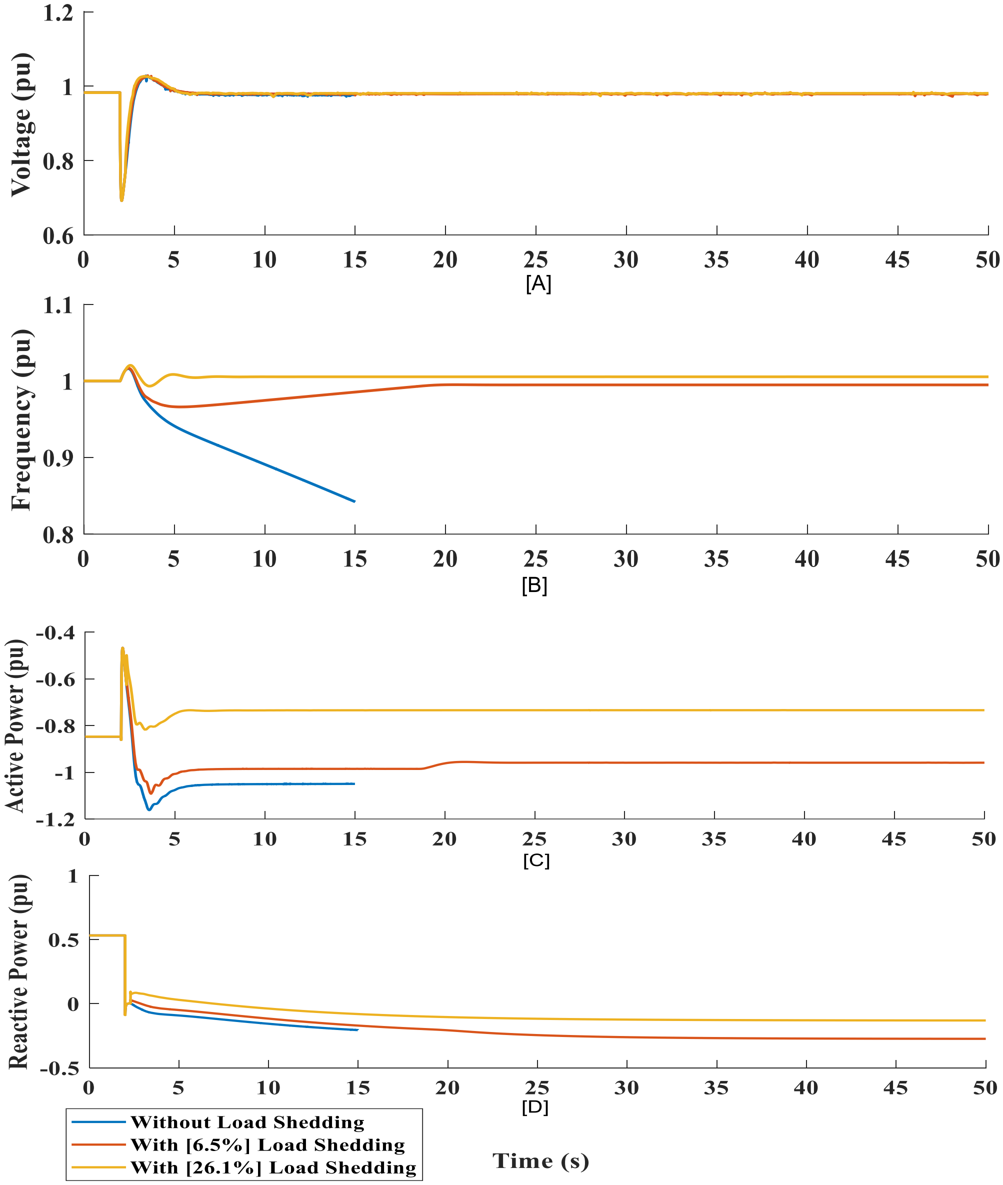


Fig 4-6: The Output Response of the Generator at Bus 31

4.7 The dynamic behavior of Island (4)

Island (4) will be formed by disconnecting the line between Bus 6 and Bus 26 and the line between bus 6 and bus 7. Table 4-10 demonstrates the data of Island (4).

The dynamic behavior for Island (4) under the average loading conditions and the maximum loading condition is introduced in the following sections.

Table 4-10: Data of Island (4)

Bus number	Load	Generator rating
16	0.06 MW, 0.02 Mvar	0.5 MVA at 0.8 PF lag
17	0.06 MW, 0.02 Mvar	0.25 MVA at 0.8 PF lag
13	0.06 MW, 0.035 Mvar	0.25 MVA at 0.8 PF lag
14	0.12 MW, 0.08 Mvar	-
15	0.06 MW, 0.01 Mvar	-
18	0.09 MW, 0.04 Mvar	-
12	0.06 MW, 0.035 Mvar	-
11	0.045 MW, 0.03 Mvar	-
10	0.06 MW, 0.02 Mvar	-
9	0.06 MW, 0.02 Mvar	-
8	0.2 MW, 0.1 Mvar	-
7	0.2 MW, 0.1 Mvar	-
6	0.2 MW, 0.1 Mvar	

Similar to island 3, under average loading conditions, loads at buses 7 and 9 will be disconnected according to LSA. Fig 4-7, Fig 4-8 and Fig 4-9 illustrate the response of the local DGs at buses 13, 16 and 17 in three cases: without applying the LSA (without disconnecting any loads), disconnecting the load at bus 9 only (6% load shedding) and applying the LSA.

For the first case, the load demand is higher than the DGs capability and, so, the frequency of DGs in the Island 3 will decrease until it is disconnected by the protection system as shown in Fig 4-7-B, Fig 4-8-B and

Fig 4-9-B. In the second case, the DGs in the island will be overloaded as shown in Fig 4-7-C, Fig 4-8-C and Fig 4-9-C and the frequency will decrease below the allowable limits as shown in Fig 4-7-B, Fig 4-8-B and Fig 4-9-B. So, in this case, the protective relaying will disconnect the DGs to prevent any damage.

After applying the LSA, the loads at busses 7 and 9 will be disconnected to supply the remaining loads with proper frequency and voltage as shown in Fig 4-7, Fig 4-8 and Fig 4-9.

In case of applying the LSA, the output active power of the generator at bus 13 is modified from -0.82 pu to -0.92 pu as shown in Fig 4-5-C, while the active power of the generators at bus 16 and bus 17 is modified from -0.69 pu and -0.38 pu to -0.79 pu and -0.49 pu, respectively, as shown in Fig 4-8-C and Fig 4-9-C, to meet the new load requirements. The transition in the active power will cause fluctuations in the frequency as shown in Fig 4-7-B, Fig 4-8-B and Fig 4-9-B.

For the reactive power, the output reactive power of the DG at bus 13 is modified from 0.57 pu to -0.5 pu as shown in Fig 4-7-D and the reactive power for the DGs at bus 16 and bus 17 is modified from 0.33 pu and -0.57 pu to -0.05 pu and -0.8 pu, respectively, as shown in Fig 4-8-D and Fig 4-9-D to meet the new load requirements. This causes fluctuations in the voltage as shown in Fig 4-7-A, Fig 4-8-A and Fig 4-9-A.

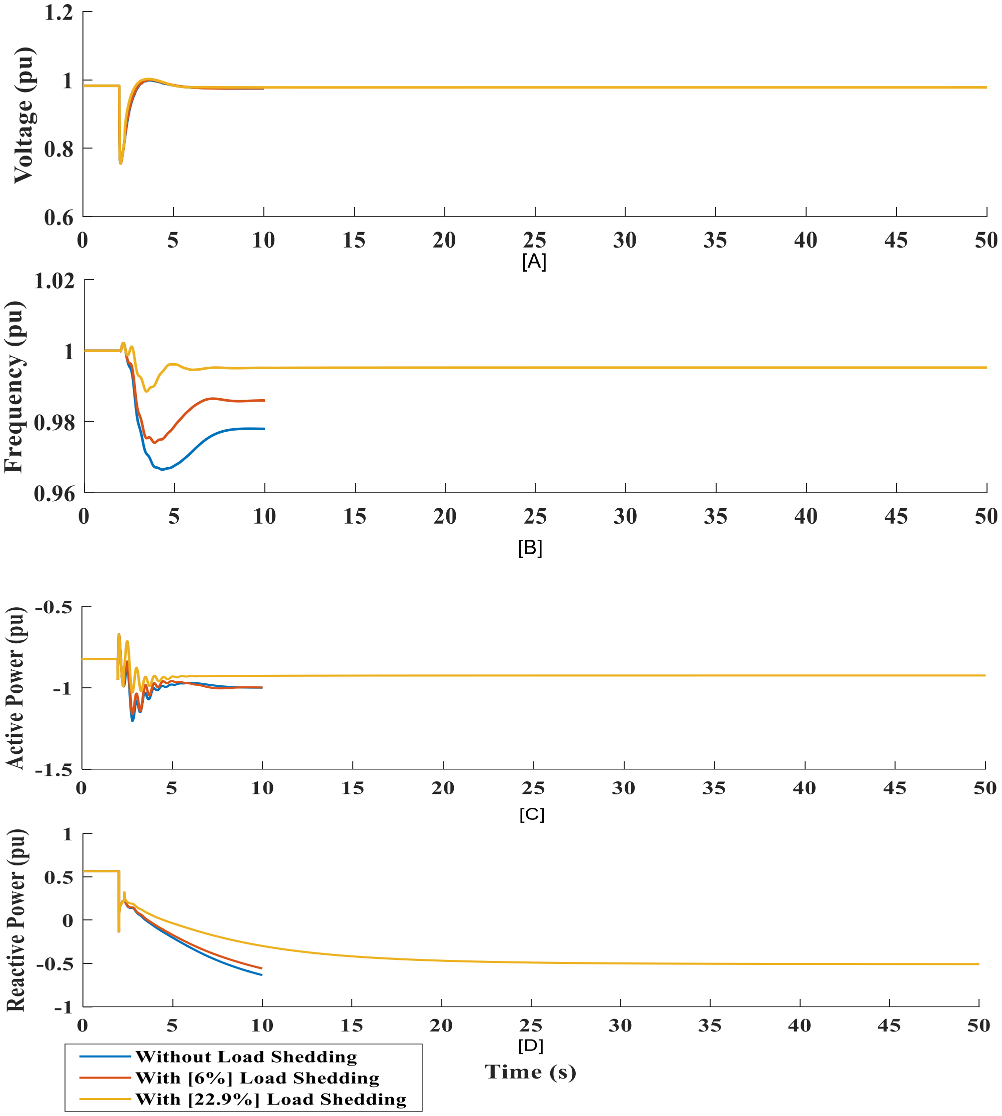


Fig 4-7: The Output Response of the Generator at Bus 13

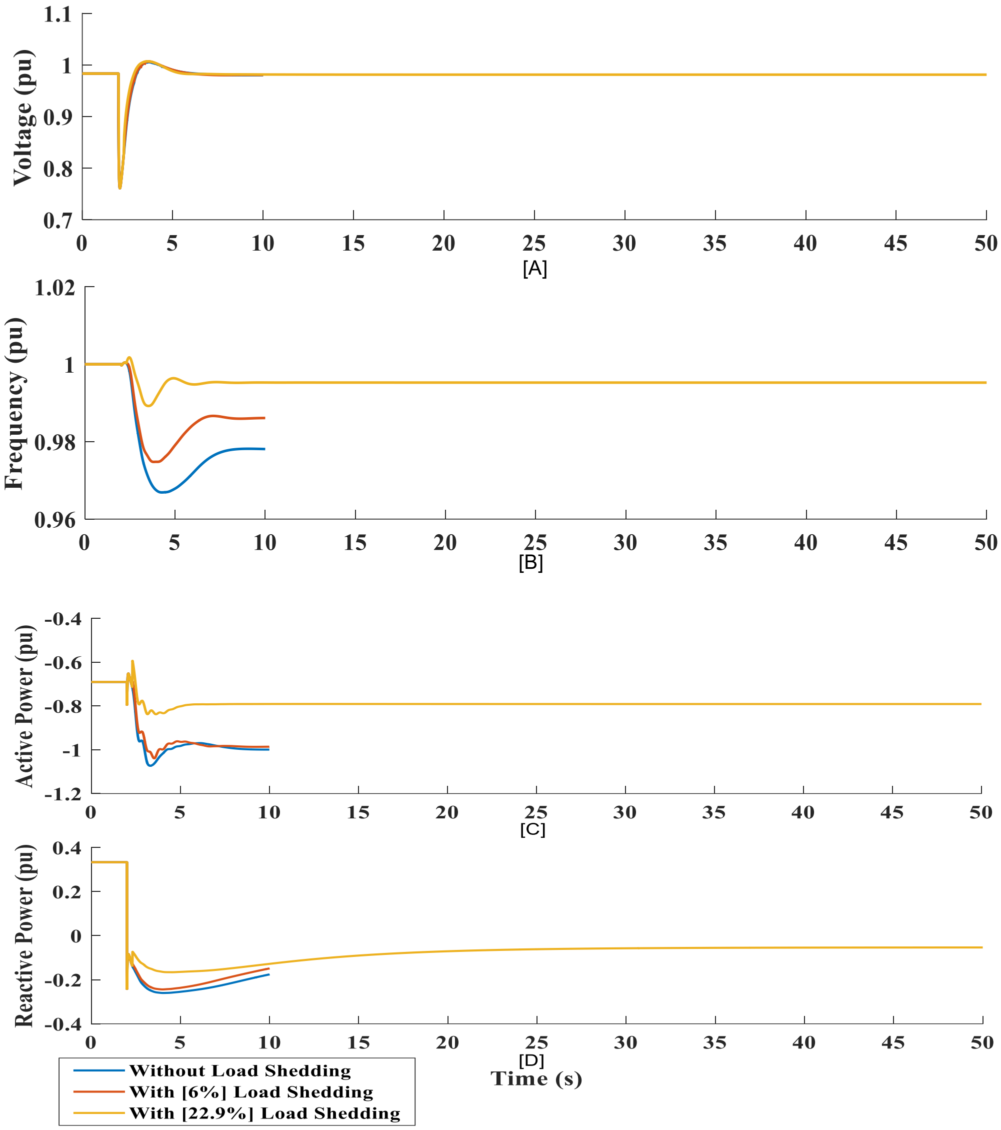


Fig 4-8: The Output Response of the Generator at Bus 16

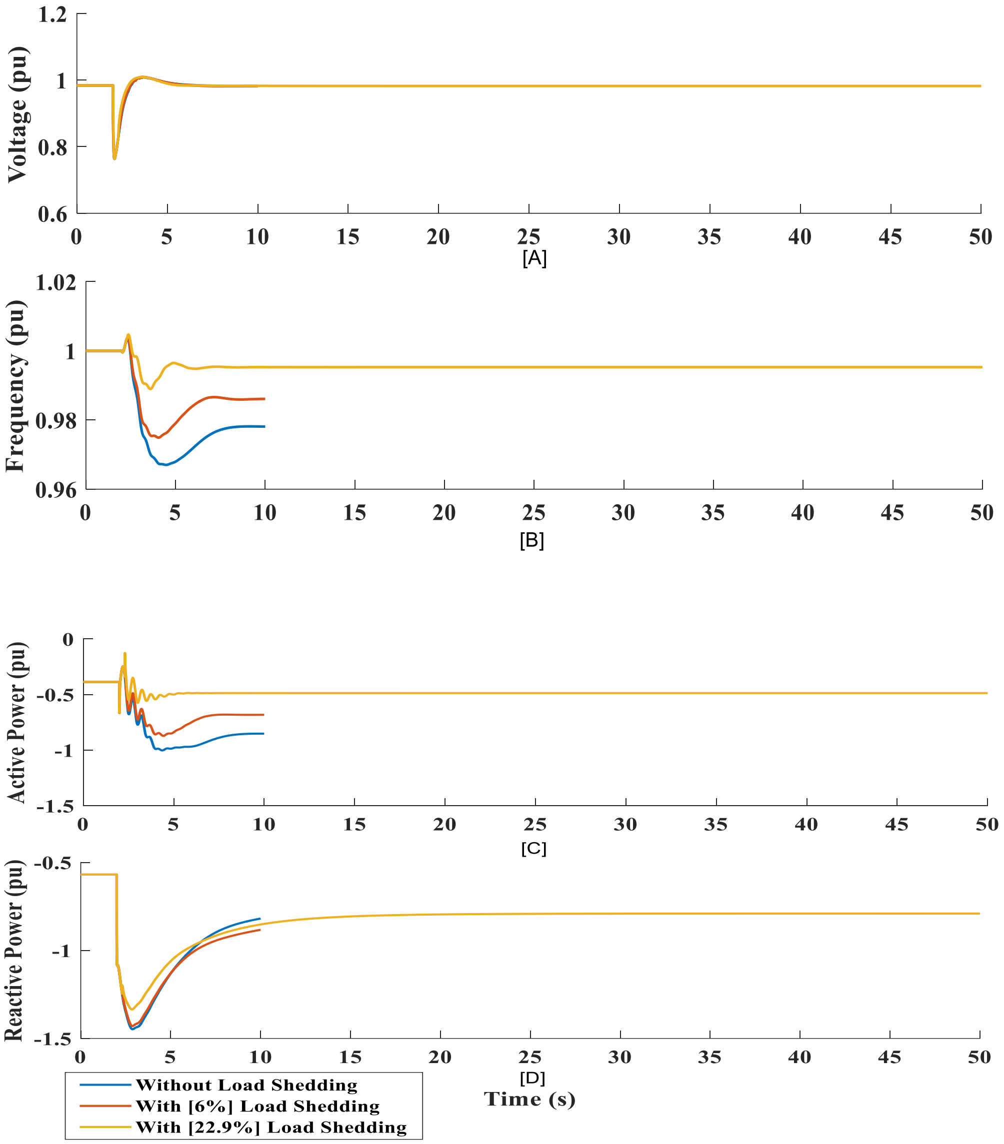


Fig 4-9:The Output Response of the Generator at Bus 17

Fig 4-7, Fig 4-8 and Fig 4-9 demonstrate the dynamic performance of the DGs in Island (4) with successful transition to island mode. This island has multi-DG units and the rotor-angle difference between generators must be monitored. Fig 4-10 illustrates the rotor angle difference between DGs in island 4. This figure confirms successful transition to island mode.

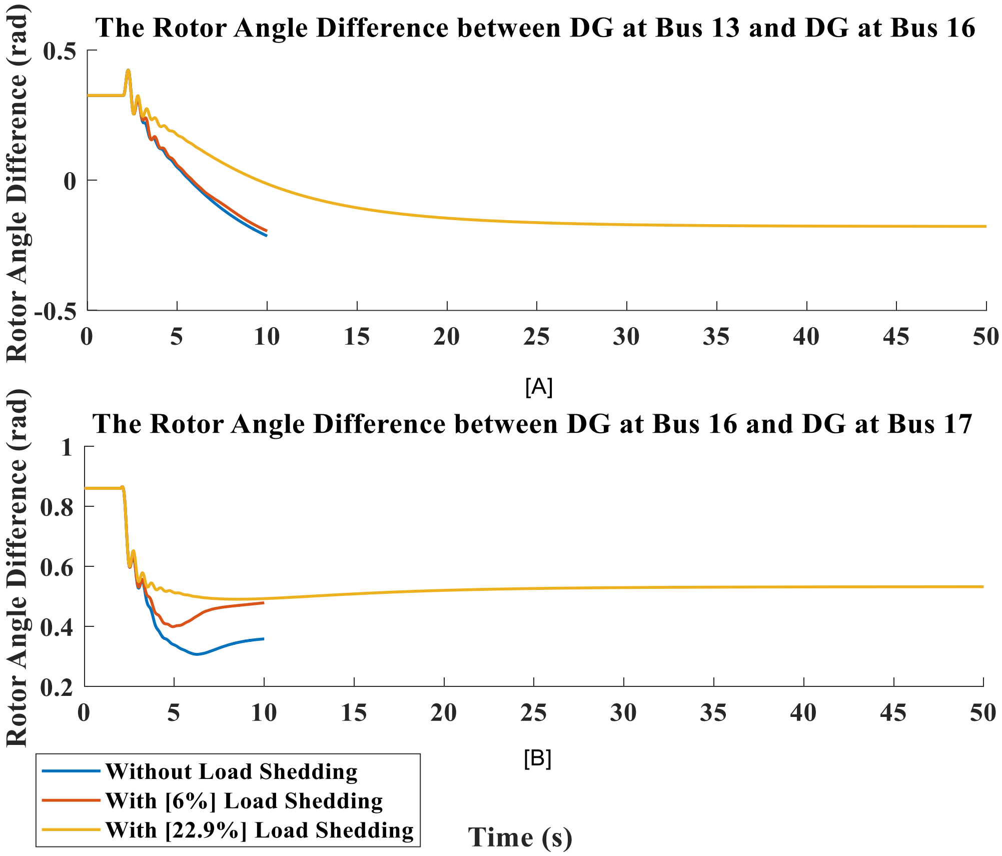


Fig 4-10: The Rotor Angle Difference between each DG in island 4

In the following chapter, a small signal stability study for all islands in the IEEE 33-bus system will be demonstrated for all loading conditions with many scenarios for the distribution system operation.

4.8 Summary

This chapter introduced the IEEE 33-bus Island configurations also the dynamic of four island at the average loading conditions. In this chapter, the timing for the transition moment is introduced. The transition moment includes change in speed droop ration in case of island 1 and island 2. The rotor angle difference for island 4 is monitored hence this island contains more than two DG units. As conclusion for this chapter, the LSA succeed to enhance the dynamic of the transition moment.

CHAPTER 5

Results of Small Signal Stability Analysis

This chapter introduces the results of the small signal stability of islands and island combinations. The mathematical algorithm is found in [52, 57]. The eigenvalue analysis is performed to all islands in the system under various loading conditions to evaluate the stability degree for the system. After that, the results are used to compare between alternative islands in the IEEE 33-bus system. The total number of islands and island combinations is 10 as detailed in Table 5-1. For these configurations, the small signal stability is evaluated for 16 loading conditions representing a daily change in the load profile. The hourly load variation through one day is shown in the load profile graph in Fig 2-2. As mention before, the 24 load cases are grouped into 16 groups according to the percentage load shedding and one case is chosen from each group.

Table 5-1: Generators and Loads in Different Island Combinations

No	Island	Generators Number	Load Number
1	Island 1	1	4
2	Island 2	1	5
3	Island 3	2 and SVC unit	8
4	Island 4	3	13
5	Island 1&2	2	9
6	Island 1&4	4	17
7	Island 3&4	5 and SVC unit	21
8	Island 1&3&4	6 and SVC unit	25
9	Island 1&2&4	5	13
10	Island 1&2&3&4	7 and SVC unit	30

The following sections discuss the small signal stability analysis for four islands to assess their stability. The analysis for islands combinations is detailed in a separate section to compare these configurations.

5.1 Small Signal Stability Analysis for Islands

To assess the degree of stability of the new isolated system, small signal stability analysis is performed for each island. The system is firstly linearized to get the system matrix. Then, the eigenvalues are calculated for the system matrix. The complex eigenvalues are formed in complex conjugate pairs. Each pair is related to an oscillatory mode. It is well known that the negative real part gives the damping of the state and the imaginary part represents the frequency of oscillations.

Small signal stability assessment relies on dominant poles. The eigenvalue (λ), the frequency (ω) and damping factor (ζ) of any eigenvalue are calculated by equations (5-2) and (5-3), respectively [58].

$$\lambda=\alpha+j*\beta \qquad (5\text{-}1)$$

$$\omega = \sqrt{\alpha^2 + \beta^2} \qquad (5\text{-}2)$$

$$\zeta = \frac{-\alpha}{\sqrt{\alpha^2 + \beta^2}} \qquad (5\text{-}3)$$

5.1.1 Small Signal Stability analysis of Island 1

Table 5-2 shows the active power of loads, percentage load shedding and the shed loads for island 1 with increasing the percentage loading. This island contains one generating unit. The limit of active power generation for this island is 0.33776 MW. The load shedding algorithm is activated only for loadings of 0.95 and 1 pu. So, this island is the best island to evaluate the effect of increasing or decreasing percentage loading.

Table 5-2: Island (1) Summary Table

Percentage Loading	Load Active Power (MW)	Remaining load active power (MW)	Percentage load shedding	Shed loads
0.55	0.198	0.198	0	0
0.59	0.2124	0.2124	0	0
0.63	0.2268	0.2268	0	0
0.7	0.252	0.252	0	0
0.72	0.2592	0.2592	0	0
0.73	0.2628	0.2628	0	0
0.76	0.2736	0.2736	0	0
0.77	0.2772	0.2772	0	0
0.82	0.2952	0.2952	0	0
0.84	0.3024	0.3024	0	0
0.87	0.3132	0.3132	0	0
0.89	0.3204	0.3204	0	0
0.91	0.3276	0.3276	0	0
0.93	0.3348	0.3348	0	0
0.95	0.342	0.285	16.667	5
1	0.36	0.3	16.667	5

The dominant-eigenvalues locations of this island are indicated in Fig 5-1. The important eigenvalues to be monitored are indicated separately in Fig 5-2. With the load variation, the eigenvalue moves slightly from one location to the other. The following remarks can be observed from this figure:

1. The locations of some poles change towards the stable region by increasing the load such as Eigenvalues (2) and (3).
2. The locations of some Eigenvalues remain the same regardless of the load variation such as Eigenvalue (1). The maximum participating factor for this pole is related to the turbine, which is slow by nature.
3. The locations of some Eigenvalues move towards unstable region when the load increases such as Eigenvalue (5) and (6) in Fig 5-1.

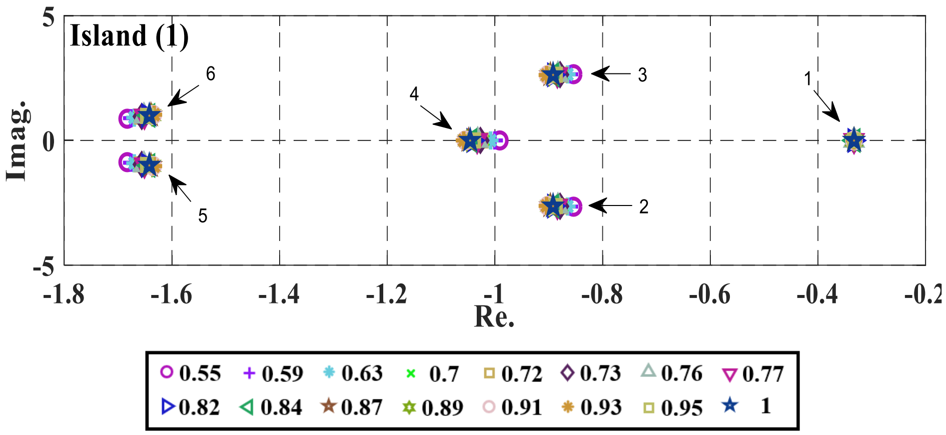


Fig 5-1: Behavior of Eigenvalues in Island (1)

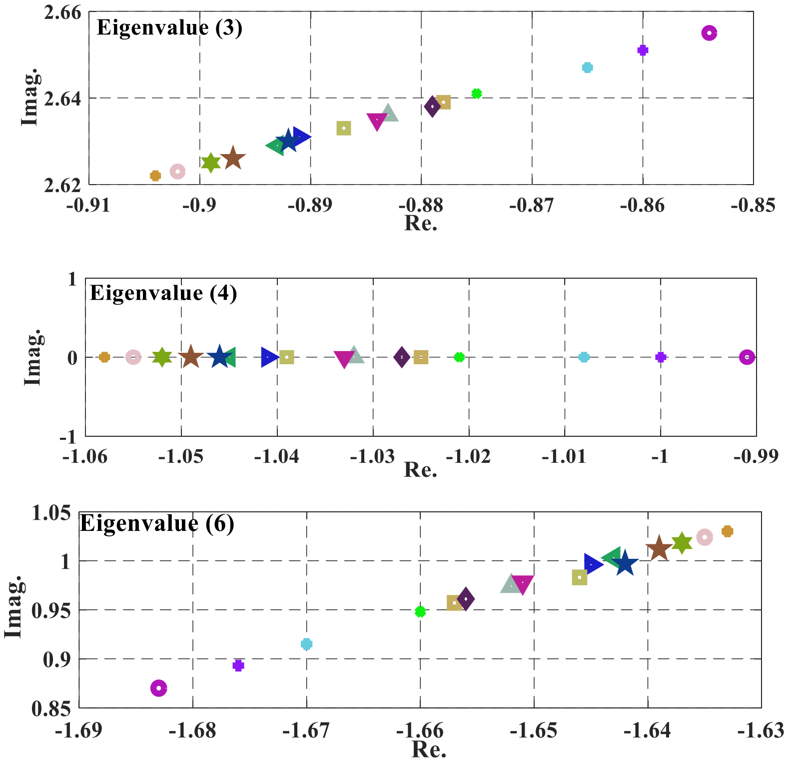


Fig 5-2: Eigenvalues for Island (1) in Detail

For this case, the important Eigenvalues to be monitored are those moving towards the unstable region. These eigenvalues are Eigenvalues (5) and (6).

5.1.2 Small Signal Stability analysis of Island 2

Similar to island 1, the active power limit for the DG is 0.33776 MW. Table 5-3 indicates the active power of loads, percentage load shedding and the shed loads for island 2. Fig 5-3 demonstrates island (2) dominant eigenvalues and Fig 5-4 indicates the important eigenvalue to be monitored in this island, i.e., Eigenvalue (6).

Table 5-3: Island (2) Summary Table

Percentage Loading	Load Active Power (MW)	Remaining load active power (MW)	Percentage Load Shedding	Shed loads
0.55	0.253	0.253	0	0
0.59	0.2714	0.2714	0	0
0.63	0.2898	0.2898	0	0
0.7	0.322	0.322	0	0
0.72	0.3312	0.3312	0	0
0.73	0.3358	0.3358	0	0
0.76	0.3496	0.2812	19.56	22
0.77	0.3542	0.2849	19.56	22
0.82	0.3772	0.3034	19.56	22
0.84	0.3864	0.3108	19.56	22
0.87	0.4002	0.3219	19.56	22
0.89	0.4094	0.3293	19.56	22
0.91	0.4186	0.3367	19.56	22
0.93	0.4278	0.2604	39.13	22,19
0.95	0.437	0.266	39.13	22,19
1	0.46	0.28	39.13	22,19

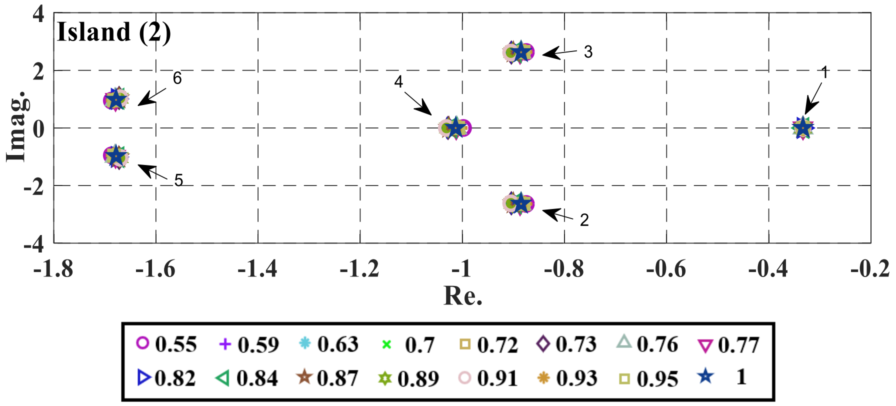


Fig 5-3: Behavior of Eigenvalues in Island (2)

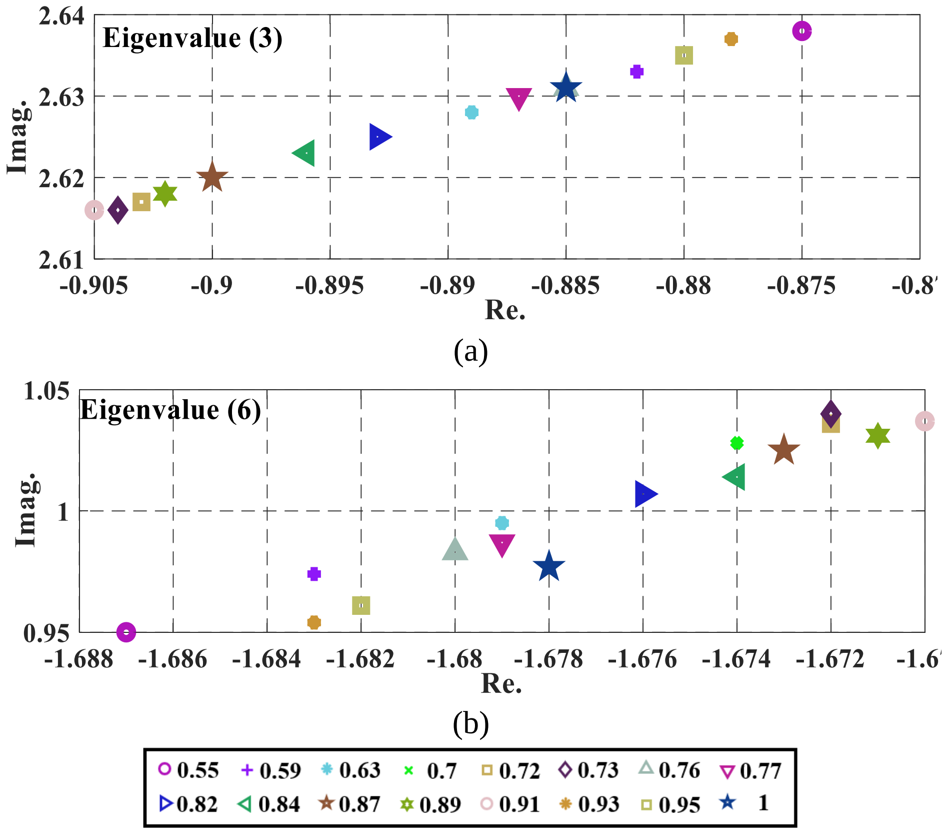


Fig 5-4: Eigenvalues for Island (2) in Detail

With the load variation, the load shedding algorithm performs certain changes in the island and, thus, the eigenvalues locations do not follow a certain tendency as shown in Fig 5-4.

Table 5-4: Island (3) Summary Table

Percentage loading	Generation Active power	Load P	P_{conn}	LS %	Disconnected loads
0.55	0.507	0.51	0.506	0	-
0.59	0.507	0.54	0.472	13.043	27, 26
0.63	0.507	0.58	0.504	13.043	27, 26
0.7	0.507	0.64	0.476	26.087	33, 28, 27, 26
0.72	0.507	0.66	0.490	26.087	33, 28, 27, 26
0.73	0.507	0.67	0.496	26.087	33, 28, 27, 26
0.76	0.507	0.7	0.494	29.348	32, 26
0.77	0.507	0.7	0.501	29.348	32, 26
0.82	0.507	0.75	0.484	35.870	32, 27, 26
0.84	0.507	0.77	0.496	35.870	32, 27, 26
0.87	0.507	0.80	0.487	39.130	29, 33, 28, 27, 26
0.89	0.507	0.82	0.498	39.130	29, 33, 28, 27, 26
0.91	0.507	0.88	0.482	42.391	32, 28, 27, 26
0.93	0.507	0.86	0.493	42.391	32, 28, 27, 26
0.95	0.507	0.87	0.504	42.391	32, 28, 27, 26
1	0.507	0.92	0.470	48.913	32, 33, 28, 27, 26

5.1.3 Small Signal Stability analysis of Island 3

Island (3) has 24 states and, thus, the number of eigenvalues is 24. Fig 5-5 illustrates the variations of dominant eigenvalues with load variations in this island. Some eigenvalues, such as 1, 3 and 4, have almost the same locations despite the change in loading conditions as shown in Fig 5-6.

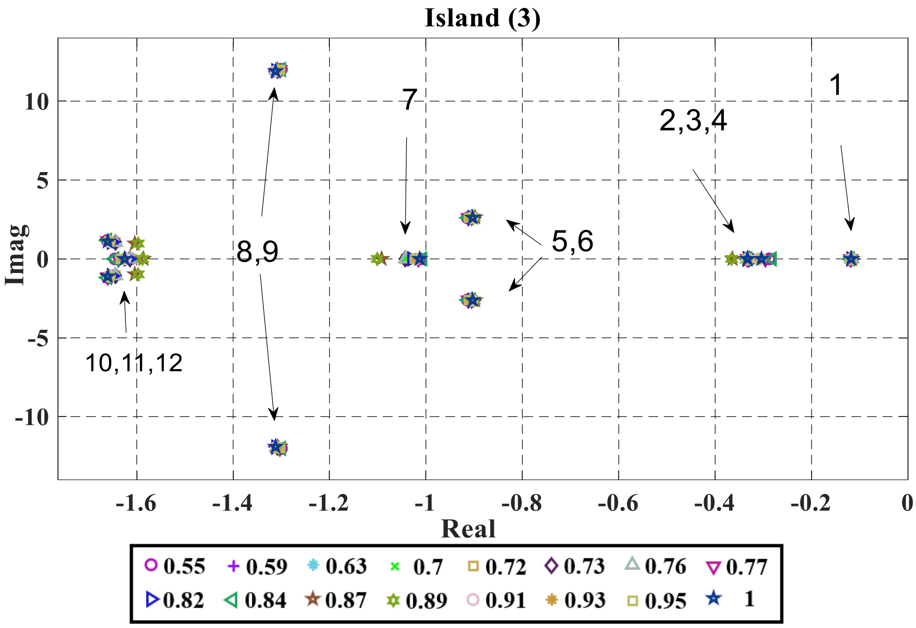


Fig 5-5: Behavior of Eigenvalues in Island (3)

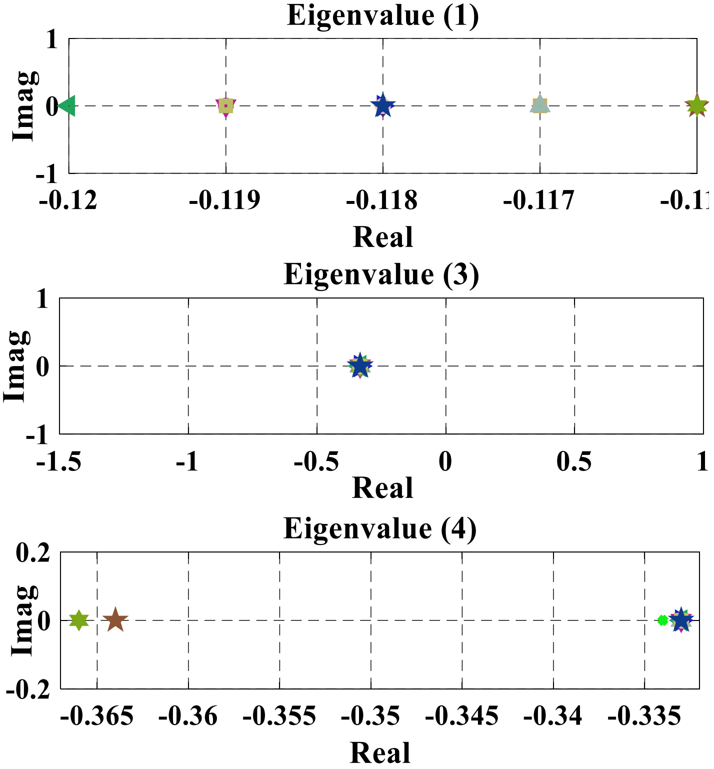


Fig 5-6: Eigenvalues 1, 3 and 4 for Island (3) in Detail

Fig 5-7 demonstrates eigenvalue (2) and eigenvalue (7) with different loading conditions. The damping factor of these eigenvalues is 1.0. The moving trend of these eigenvalues is toward the stable region with increasing the connected loads and after applying the load shedding.

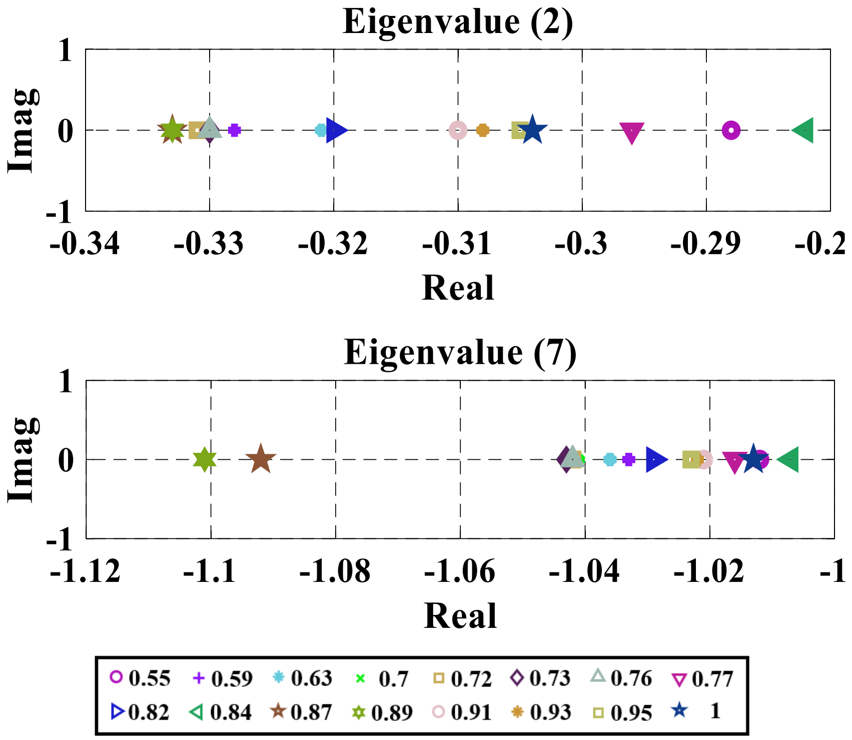


Fig 5-7: Eigenvalues 2 and 7 for Island (3) in Detail

The eigenvalues in Fig 5-8 have damping factors less than 1. So, it is important to carefully monitor these eigenvalues because of their oscillatory nature. Load shedding algorithm succeeded to limit variations of eigenvalue (6) within the same margin despite the loading variation. The moving trend of eigenvalue (9) is toward the instability region.

As a conclusion, the island is stable for all loading conditions as shown in Fig 5-6. This means that the remaining loads will be supplied and operated with an acceptable level of stability. Similar results are obtained for other islands.

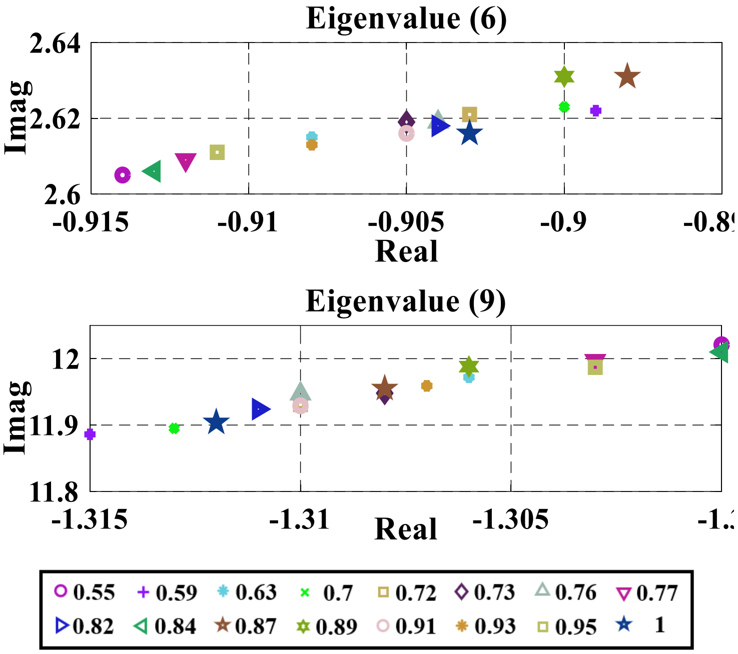


Fig 5-8: Eigenvalues 6 and 9 for Island (3) in Detail

5.1.4 Small Signal Stability analysis of Island 4

The difference of this island is that it has multi DG units and, thus, it has more eigenvalues than the previous islands. The existence of multi DGs increases the probability of instability conditions.

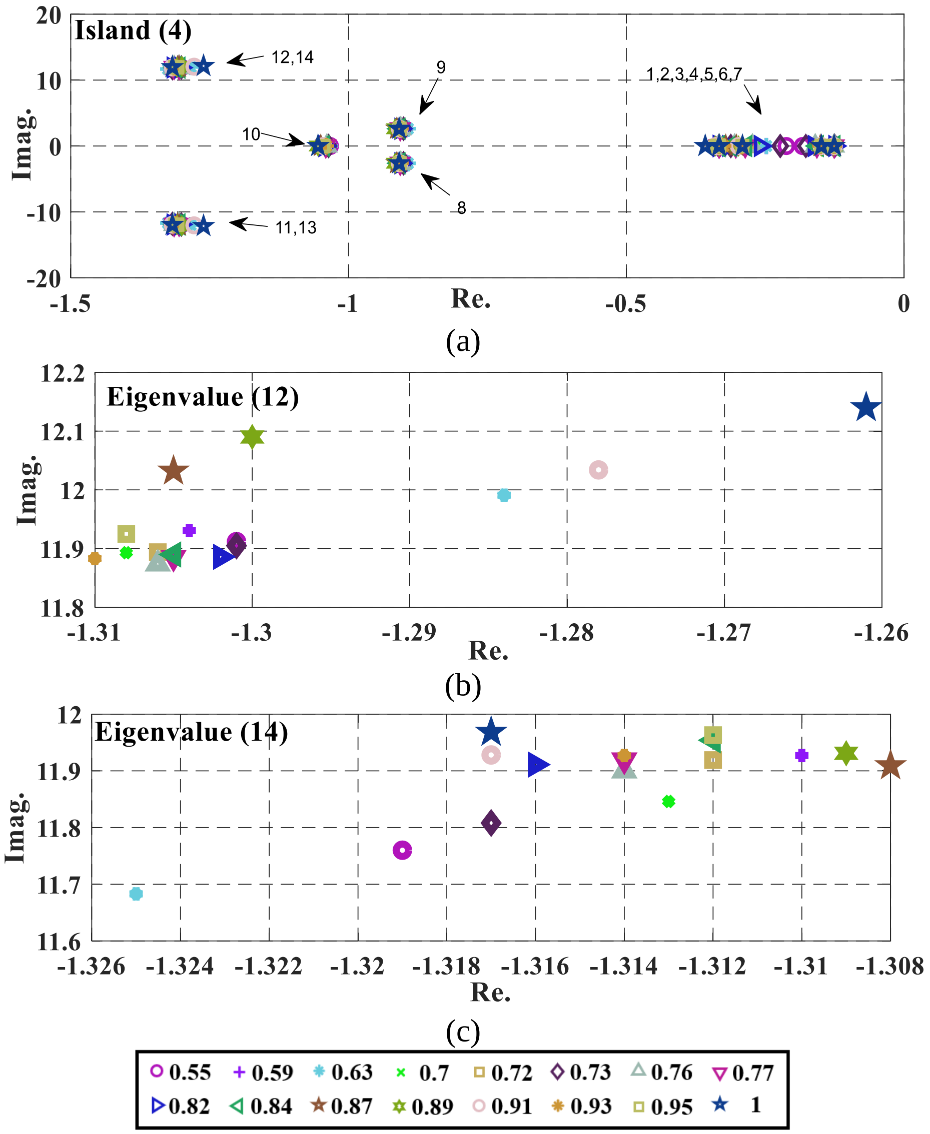
Table 5-5 indicates the summary of island (4) power. The limit of DG capacity in this island is 0.676 MW. Figure 5-9 indicates the dominant Eigenvalues in island (4).

Table 5-5: Island (4) Summary Table

Percentage Loading	Load Active Power (MW)	Remaining load active power (MW)	Percentage Load Shedding	Shed loads
0.55	0.62	0.62	0	-
0.59	0.67	0.67	0	-
0.63	0.72	0.59	17.62	7
0.7	0.79	0.65	17.62	7
0.72	0.82	0.67	17.62	7
0.73	0.83	0.64	22.91	7,9
0.76	0.86	0.67	22.91	7.9
0.77	0.87	0.67	22.91	7,9
0.82	0.93	0.67	28.19	7,9,10
0.84	0.95	0.65	32.16	7, 9, 10, 11
0.87	0.99	0.67	32.16	7, 9, 10, 11
0.89	1.01	0.67	33.48	7, 9, 10, 12
0.91	1.03	0.67	35.24	7, 8
0.93	1.06	0.66	37.44	7, 9, 10, 11, 12
0.95	1.08	0.67	37.44	7, 9, 10, 11, 12
1	1.14	0.68	40.53	7, 8, 9

5.1 The Results of Small Signal Stability for Islands Combinations

Although combining islands gives opportunities for decreasing the percentage load shedding meaning that more loads can be supplied by local DGs, the eigenvalues of the new configurations must be monitored to guarantee the stability of new systems.



(a)

(b)

(c)

Fig 5-9: Behavior of Eigenvalues in Island (4)

Table 5-6 indicates all islands and island combinations scenarios for intentional islanding. Small signal stability study has been performed for individual islands and their combinations to assess the steady-state stability for these configurations.

Table 5-6: System Scenarios for Intentional Islanding

Scenarios	Islands
1	Islands (1) & (2) & (3) & (4)
2	Islands (1&2) & (3) & (4)
3	Islands (1&4) & (2) & (3)
4	Islands (1) & (2) & (3& 4)
5	Islands (1&2) & (3&4)
6	Islands (1&3&4) & (2)
7	Islands (1&2&4) & (3)
8	Islands (1&2&3&4)

Table 5-7 indicates a summary of the results of small signal stability study. The number of eigenvalues increases with island combinations due to the increase of the number of machines. Generally, the island with a single DG unit has more damping than the island with multi DG units.

For IEEE 33-bus system, to assess the degree of stability for every scenario, minimum damping factors are calculated for the 16-loading cases with 10 different islands (individual islands and islands combinations). Fig 5-10 indicates the minimum damping factor (ζ) for different loading conditions and different islands.

From Fig 5-10, all islands, except island (1) and island (2), have multi DG units. The damping factors for all configurations, except island (1) and island (2), are at the same level. Thus, the factor to choose a certain scenario will be the percentage load shedding that is indicated in Fig 4-2. It is obvious that choosing islands combination will not affect the system stability but will increase the supplied loads.

Table 5-7: Summary of Small Signal Stability Study for All Configurations

Island configuration	**Total No. of eigenvalues**	**No of dominant eigenvalues**	**Smallest damping factor for all cases**		
			Damping factor	Eigenvalue	Loading conditions
Islands (1)	12	7	0.30621	-0.854-2.655i	0.55
Islands (2)	12	7	0.31482	-0.875-2.638i	0.55
Islands (3)	24	14	0.10752	-1.3-12.021i	0.55
Islands (4)	36	21	0.10332	-1.261-12.14i	1
Islands (1&2)	24	14	0.11371	-1.377-12.031i	1
Islands (1&4)	48	28	0.11013	-1.344-12.129i	0.82
Islands (3&4)	60	35	0.10617	-1.297-12.147i	0.76
Islands (1&2&4)	60	35	0.11143	-1.373-12.245i	0.72
Islands (1&3&4)	72	42	0.10943	-1.338-12.154i	0.93
Islands (1&2&3&4)	84	49	0.10925	-1.339-12.173i	0.55

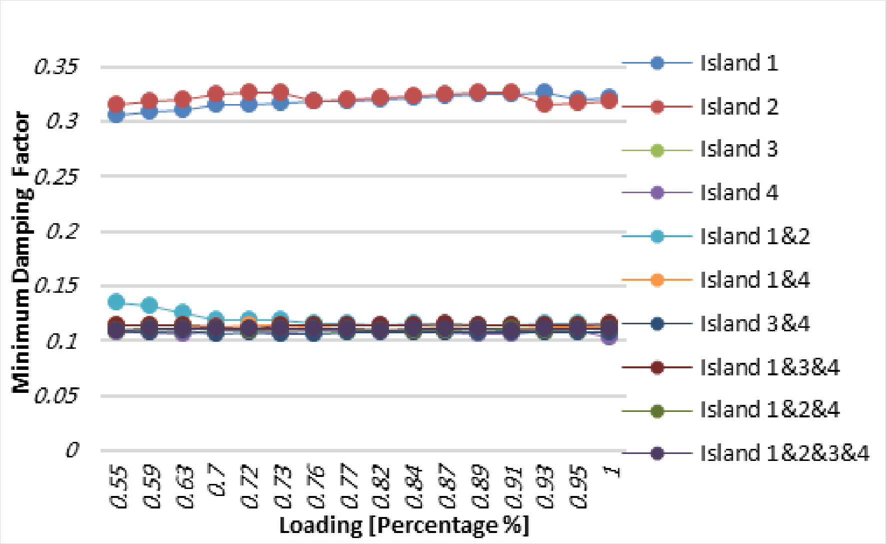


Fig 5-10: Minimum Damping Factor for Islands and Islands Combinations

CHAPTER 6

Conclusions and Suggestions for Future Work

6.1 Conclusions

The dynamic transition to island operation is extensively investigated for different islands regarding the IEEE 33-bus system. With 50% pentation level of DGs units and 30% maximum limit for load shedding for each island, a successful transition to island mode is achieved.

A load shedding algorithm is proposed to guarantee maintaining the service for the maximum possible number of customers. This is achieved via disconnecting the customers with low priority at the correct time. The dynamic behavior during transition to island mode and small signal study is extensively investigated to prove the visibility of the introduced load shedding algorithm. The results showed that the load shedding algorithm can maintain service by disconnecting appropriate customers in the proper time. It was also possible to regulate the frequency to match network frequency by modifying the governor mode or droop characteristic. This would facilitate the restoring of the system after any intentional islanding process.

Small signal stability study proved stable steady state operation of the resulting isolated systems. Eigenvalues tend to move within a small margin after applying the load shedding algorithm. The obtained results of investigating the damping factor proved the success of the load shedding algorithm to maintain the steady state stability and the minor effect on the Eigenvalues shift. Combining islands increases the reliability of the system but needs many control signals to form the final configuration.

6.2 Suggestions for Future work

The following points could be investigated in future studies:

1. Converting the system to fully automated system considering possibility of islanding.
2. Studying the effect of renewable energy resources instead of the GAST turbine model.
3. Studying the effect of intentional islanding on the protection system.

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Publications

Conference

1- A. M. Elkholy, H. A. A. El-Ghany, and A. M. Azmy, "A proposed load shedding mechanism for enhancing intentional-islanding dynamics of distribution systems," Nineteenth International Middel East Power System Conference (MEPCON), 2017, pp. 870-875.

2- A. M. Elkholy, H. A. A. El-Ghany, and A. M. Azmy, "An Advanced Load Shedding Algorithm to Enhance Intentional-Islanding Dynamics," Twinty International Middel East Power System Conference (MEPCON), 2018.

Journal

3- A. M. Elkholy, H. A. A. El-Ghany, and A. M. Azmy, "Enhancing Distribution System Reliability using Intentional Islanding," Electric Power Components and Systems. (under review)

Appendices

Appendix A: 33-Bus System Data

Table A: 33-Bus System Data

Line Data				Bus Data		
From	To	R (Ω)	X_L(Ω)	Bus	P (MW)	Q (Mvar)
1	2	0.0575	0.0293	2	0.1	0.06
2	3	0.3076	0.1567	3	0.09	0.04
3	4	0.2284	0.1163	4	0.12	0.08
4	5	0.2378	0.1211	5	0.06	0.03
5	6	0.511	0.4411	6	0.06	0.02
6	7	0.1168	0.3861	7	0.2	0.1
7	8	0.4438	0.1467	8	0.2	0.1
8	9	0.6426	0.4617	9	0.06	0.02
9	10	0.6514	0.4617	10	0.06	0.02
10	11	0.1227	0.0405	11	0.045	0.03
11	12	0.2336	0.081	12	0.06	0.035
12	13	0.9159	0.7206	13	0.06	0.035
13	14	0.3379	0.4448	14	0.12	0.08
14	15	0.3687	0.3282	15	0.06	0.01
15	16	0.4657	0.34	16	0.06	0.02
16	17	0.8042	1.0738	17	0.06	0.02
17	18	0.4567	0.3581	18	0.09	0.04
2	19	0.1023	0.0976	19	0.09	0.04
19	20	0.9385	0.8457	20	0.09	0.04
20	21	0.2555	0.2985	21	0.09	0.04
21	22	0.4423	0.5848	22	0.09	0.04
3	23	0.2815	0.1924	23	0.09	0.05
23	24	0.5602	0.4424	24	0.42	0.2
24	25	0.559	0.4374	25	0.42	0.2
6	26	0.1267	0.0645	26	0.06	0.025
26	27	0.1773	0.0903	27	0.06	0.025
27	28	0.6607	0.5826	28	0.06	0.02
28	29	0.5017	0.4371	29	0.12	0.07
29	30	0.3166	0.1613	30	0.2	0.6
30	31	0.608	0.6009	31	0.15	0.07
31	32	0.1937	0.2258	32	0.21	0.1
32	33	0.2127	0.3308	33	0.06	0.04

Appendix B: Generator Model

Table B: Generator model

Generator ID		GEN03	GEN02	GEN08	GEN06	GEN01
Bus		13	31	30	16, 20, 23	17
Name	units					
H	s	6.54	6.54	5.06	5.06	5.148
D	MW/Hz	0	0	0	0	0
R	pu	0.0031	0.0031	0.0014	0.0014	0
xd	%	105	105	125	125	89.79
xd'	%	18.5	18.5	23.2	23.2	60
xd''	%	13	13	12	12	23
xq	%	98	98	122	122	64.6
xq'	%	36	36	71.5	71.5	64.6
xq''	%	13	13	12	12	40
xl	%	0	0	13.4	13.4	23.96
Td0'	s	6.1	6.1	4.75	4.75	7.4
Td0''	s	0.04	0.04	0.06	0.06	0.03
Tq0'	s	0.3	0.3	1.5	1.5	0
Tq0''	s	0.099	0.099	0.21	0.21	0.033

Appendix C: GAST Model

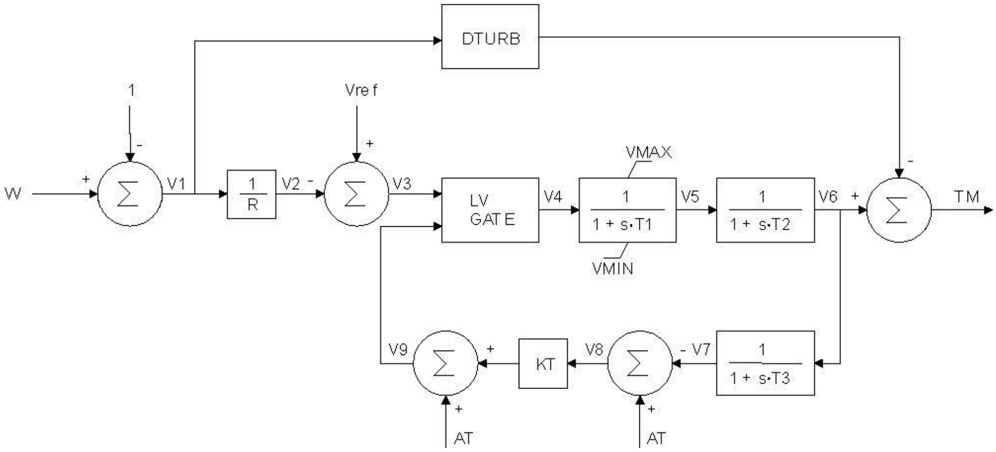

Fig C: GAST Model

Table C: GAST Model Data

Name	Unit	Description
R	pu	Speed Droop
T1	s	Governor time constant
T2	s	Combustion chamber time constant
T3	s	Exhaust gas measuring system time constant
AT	pu	Ambient Temperature Load Limit
KT	pu	Adjusts the gain of the load-limited feed-back
VMAX	pu	Maximum of turbine output
VMIN	pu	Minimum of turbine output
DTURB	pu	Speed damping constant introduced by the gas turbine motor

Appendix D: AC4A Model

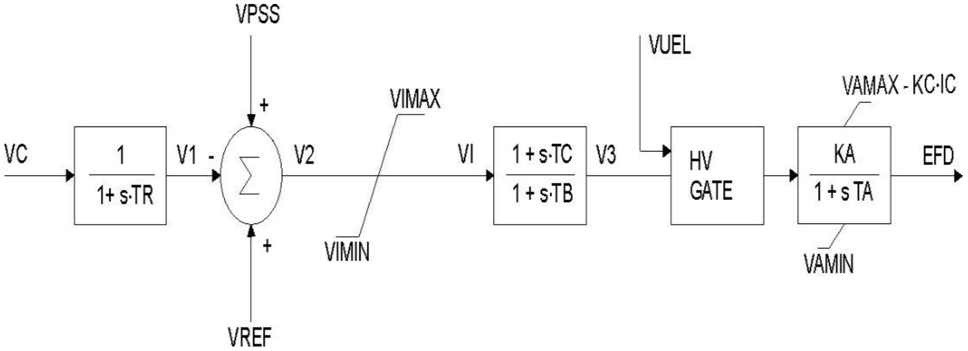

Fig D: AC4A Model

Table D: AC4A Model Data

Name	Unit	Description
TR	s	Voltage transducer filter time constant
VIMAX	pu	Maximum value of limitation of the integrator signal VI
VIMIN	pu	Minimum value of limitation of the integrator signal VI
TC	s	Voltage regulator time constant
TB	s	Voltage regulator time constant
KA	pu	Regulator gain
TA	s	Voltage regulator time constant
VRMAX	pu	Maximum limit of VR
VRMIN	pu	Minimum limit of VR
KC	pu	A parameter for calculating the maximum value of the limiter for the output signal EFD

Appendix E: LSA MATLAB Script

Contents

- load the data
- elimination 1 of the loads require high active power
- elimination 2 of the loads require high reactive power
- third stage
- check the load and generator scenarios
- output of the program

```
function load_shed=load_shedding(load,gen)
%load shedding function the input is load (act(mw)
react(mvar) name id) and
% gen (s(MVA) pf)
```

load the data

```
load_act_power=load.act;
load_react_power=load.react;
load_id=load.id;
load_numbre=length(load_act_power);
active_genration_cap=sum((gen.s).*(gen.pf));
reactive_genration_cap=sum((gen.s).*sin(acos((gen.pf))))
;
```

elimination 1 of the loads require high active power

```
id=find(load_act_power>=active_genration_cap);
load_act_power(id)=[];
load_react_power(id)=[];
load_id(id)=[];
```

elimination 2 of the loads require high reactive power

```
id=find(load_react_power>=reactive_genration_cap);
load_act_power(id)=[];
load_react_power(id)=[];
load_id(id)=[];
```

third stage

```
sum_act=0;
```

```
sum_react=0;
```

create the system scenarios

```
for n1=1:length(load_act_power)
    i=1;
    clear scenarios scenarios_names scenarios_id
    sum_act=load_act_power(n1);
    sum_react=load_react_power(n1);
    scenarios(i)=load_act_power(n1);
    scenarios_id(i)=load_id(n1);
    for n2=1:length(load_act_power)
        if n1~=n2
        if sum_act<active_genration_cap ||
sum_react<reactive_genration_cap
            i=i+1;
            sum_act=sum_act+load_act_power(n2);
            scenarios(i)=load_act_power(n2);
            scenarios_id(i)=load_id(n2);
        end
        if
sum_act>active_genration_cap||sum_react>reactive_genrati
on_cap
            sum_act=sum_act-load_act_power(n2);
            scenarios(i)=0;
            scenarios_id(i)=[];
        end
        end
    end
    scenarios_id_all(n1,:)=zeros(1,(length(load_id)));
    scenarios_id_all(n1,:)=[scenarios_id
zeros(1,(length(scenarios_id_all(n1,:))-
length(scenarios_id)))];
    scenarios_genration_value(n1,:)=scenarios;
    sum_sin(n1)=sum(scenarios);
    sum_sin_test(n1)=sum(scenarios)+(1/n1)*.001; % give
wight to the load as rink

end
```

Output of the program

```
load_shed.scenarios_id_all=scenarios_id_all;
load_shed.scenarios_genration_value=scenarios_genration_
value;
load_shed.sum_sin=sum_sin;
load_shed.sum_sin_test=sum_sin_test;
[M,scenarios_numbre] = max(sum_sin_test);%max get the
max and the number in the cell
load_shed.scenarios_numbre=scenarios_numbre;
load_shed.island_id=scenarios_id_all(scenarios_numbre,:)
;
load_shed.load_out_service=serviceload(load.id,load_shed
.island_id);
```

http://www.mathworks.com/products/matlab/

Appendix F: Eigenvalue of Island Combinations

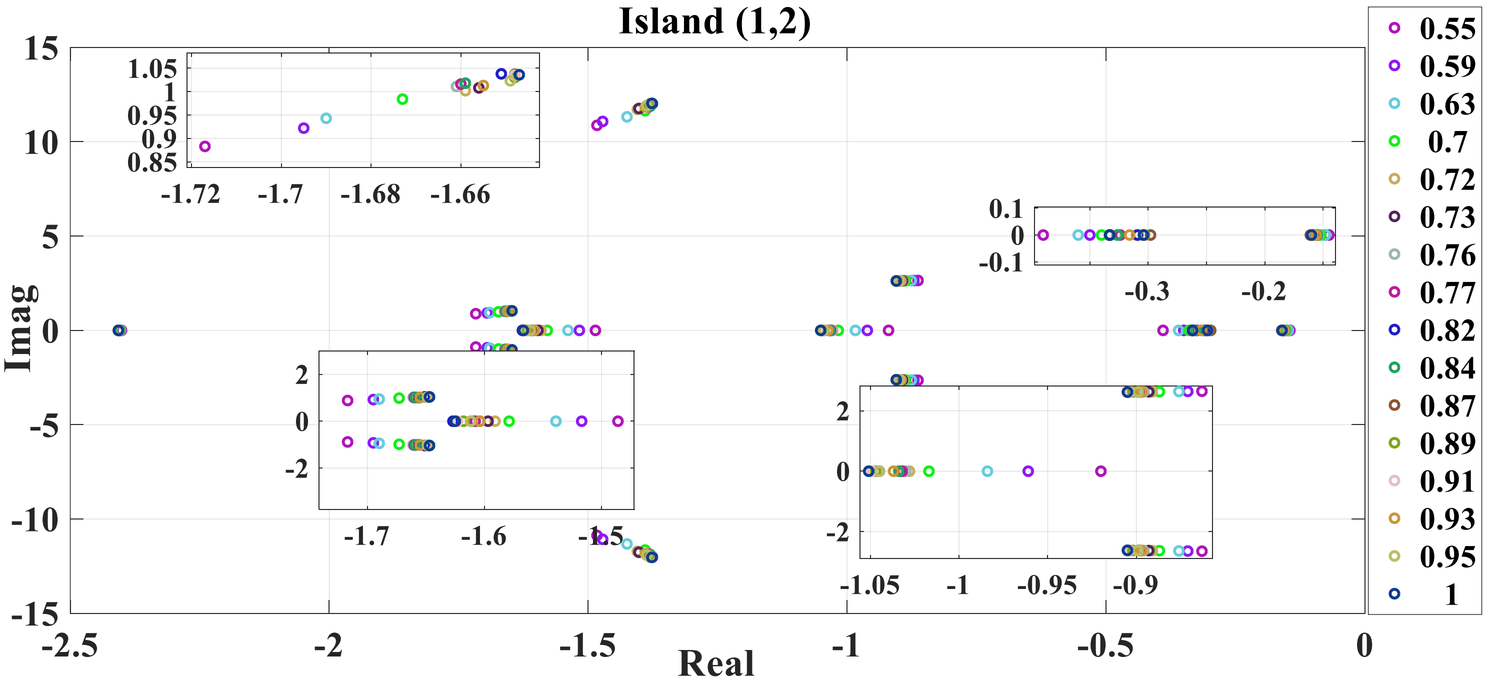

Fig F1: Eigenvalues of combined Island 1 and Island 2

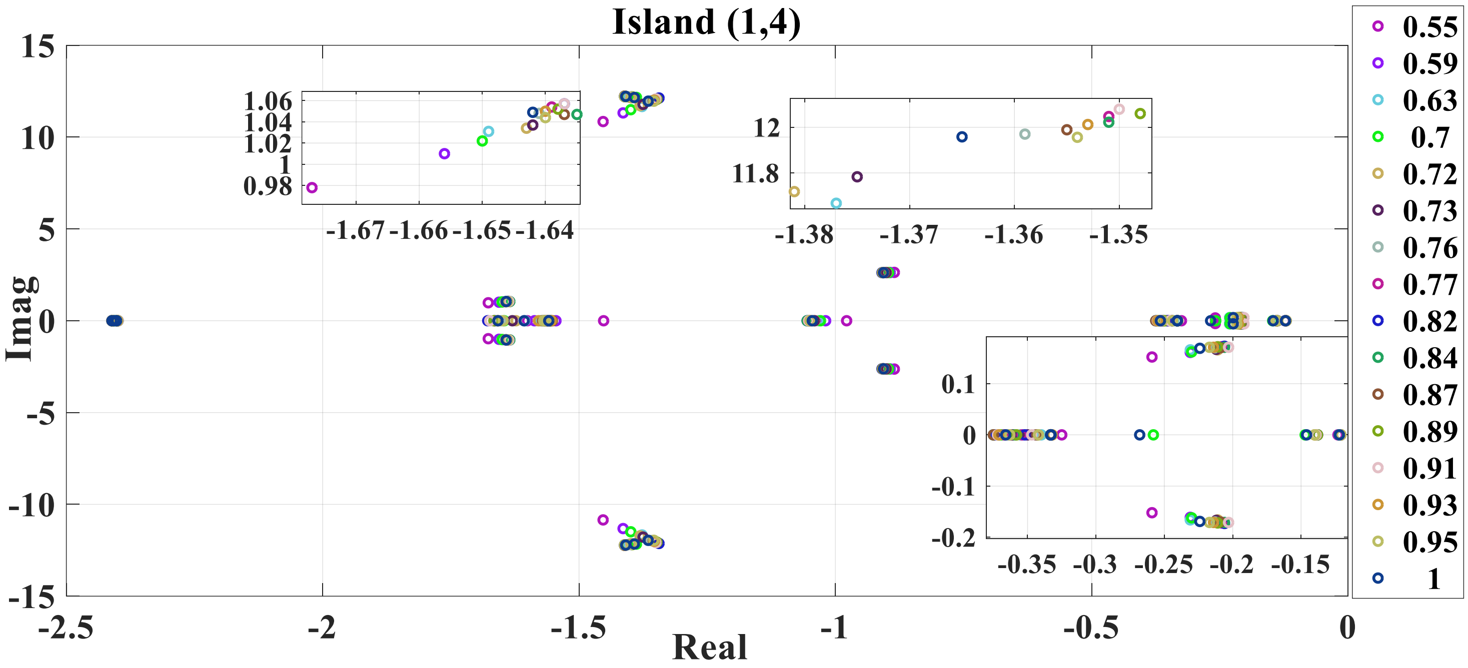

Fig F2: Eigenvalues of combined Island 1 and Island 4

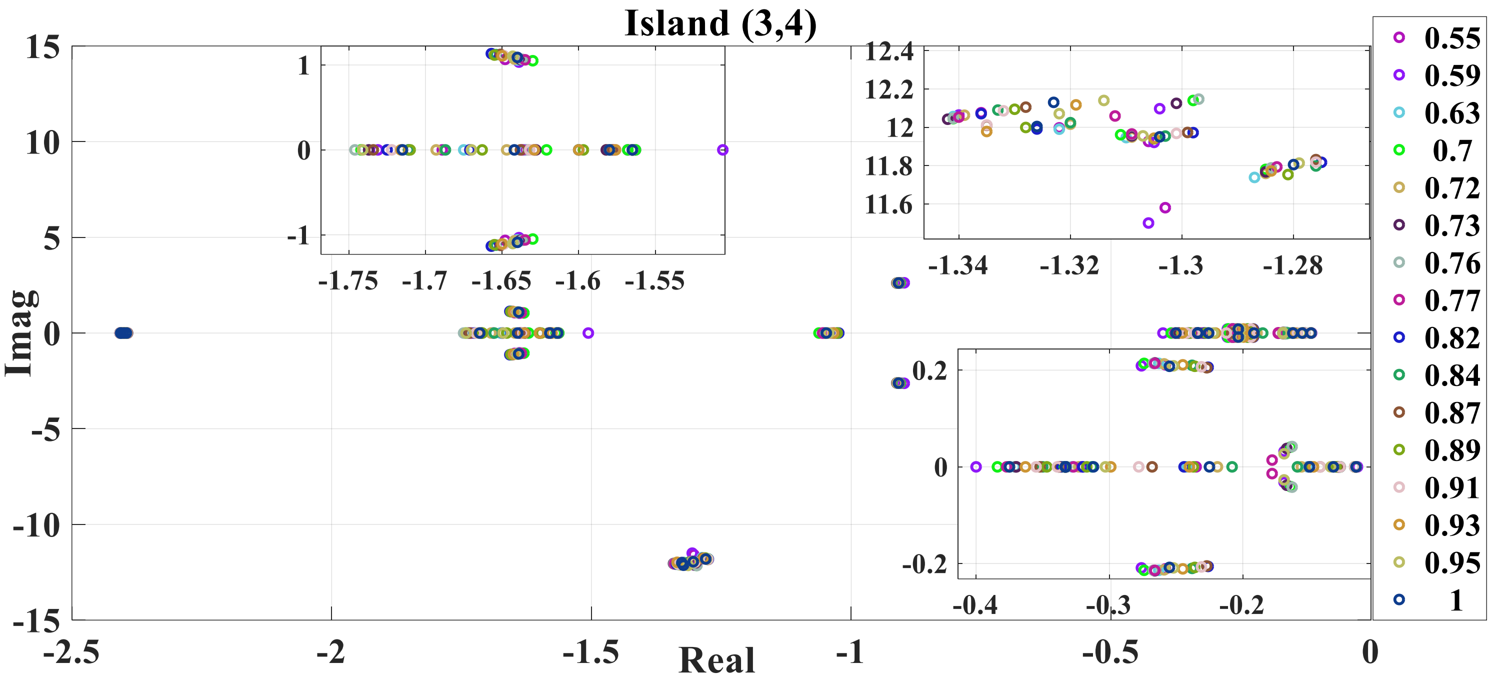

Fig F3: Eigenvalues of combined Island 3 and Island 4

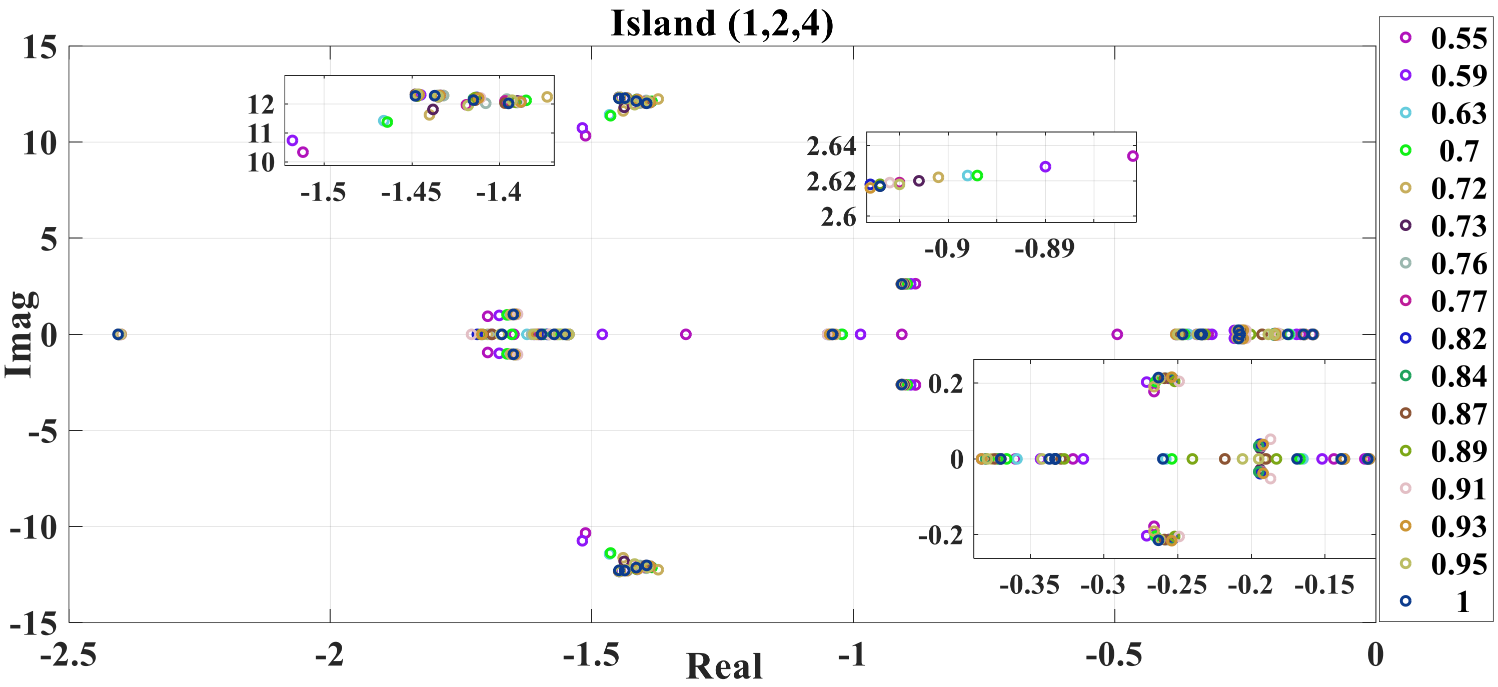

Fig F4: Eigenvalues of combined Island 1, Island 2 and Island 4

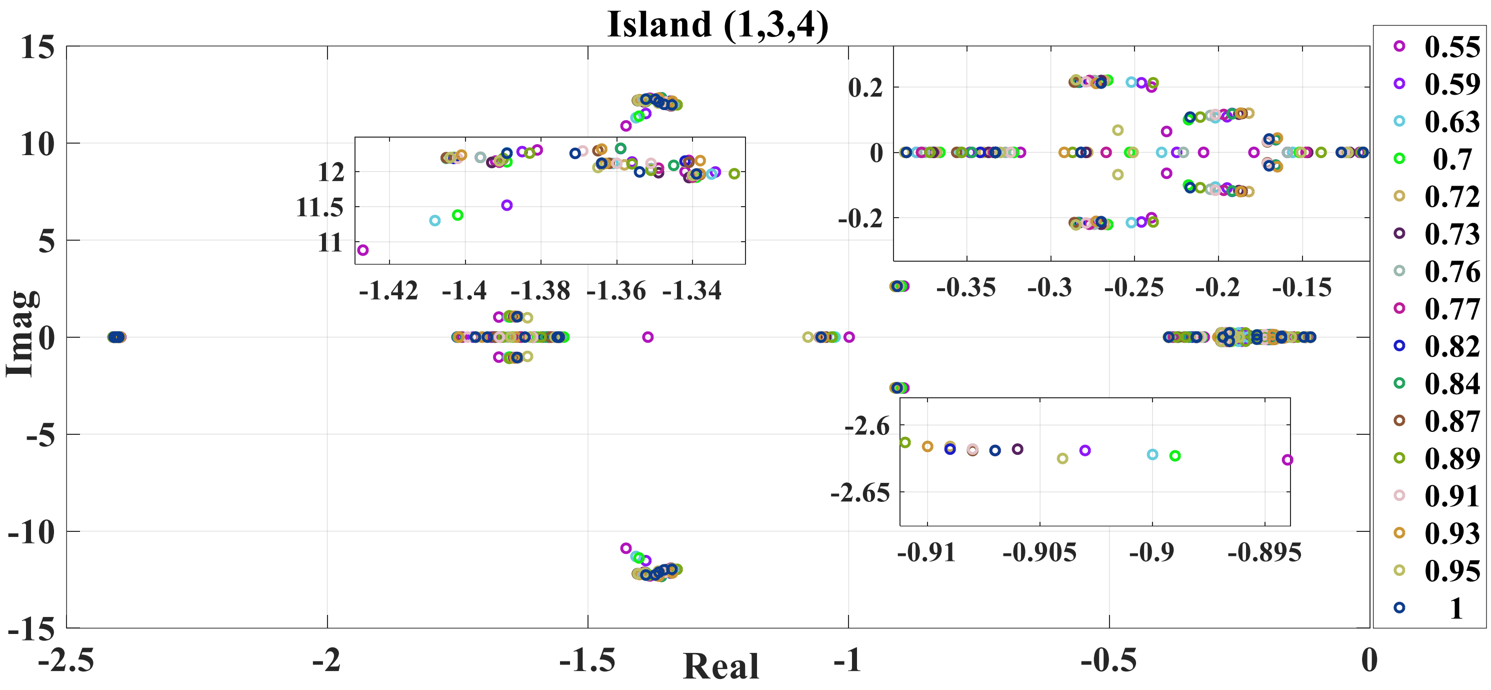

Fig F5: Eigenvalues of combined Island 1, Island 3 and Island 4

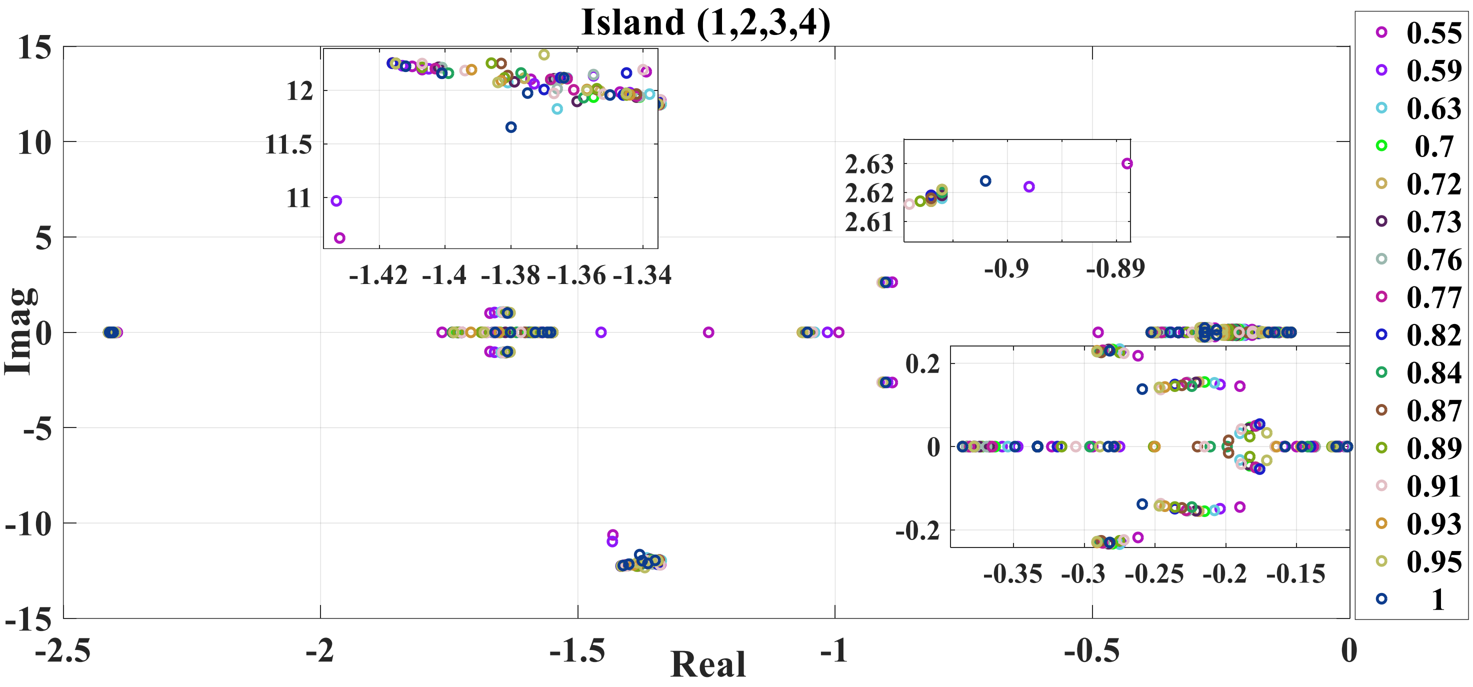

Fig F6: Eigenvalues of combined Islands 1, 2, 3 and 4

الفصل الأول: ويتناول مقدمة عن الرسالة ويشمل مقدمة عن اعتمادية الشبكة الكهربية ومقدمة عن كيفية فصل الأحمال للحفاظ على الجهد والتردد.

الفصل الثاني: ويتناول الحالة التي ستخضع للدراسة وأيضا توزيع الأحمال خلال اليوم والأماكن المُثلي التي أضيف عندها الوحدات الموزعة وأيضا التشكيلات التي تم اقتراحها للجزر.

الفصل الثالث: ويتناول الخوارزمية المقترحة للحفاظ على استمرارية الخدمة للعملاء ذوي الأولوية.

الفصل الرابع: ويتناول دراسة السلوك العابر للجزر في حالة الانتقال إلى حالة الجزر المعزولة.

الفصل الخامس: ويتناول النتائج الخاصة بدراسة مدي استقرار الجزر وأيضا مقارنة بين الجزر المنفردة وتكوينات الجزر معا.

بينما يتناول **الفصل الأخير** خلاصة ما تم التوصل إليه في هذه الدراسة وما قد ينبثق منها من نقاط بحثية تتم دراستها في المستقبل.

ملخص الرسالة

نظراً للزيادة في الطلب على الطاقة الكهربية في السنوات الأخيرة، يتجه العاملون في الشبكة الكهربية إلى الاستفادة من التطور التكنولوجي للوحدات الموزعة حيث أن إضافة تلك الوحدات الموزعة تزيد من اعتمادية نظم الطاقة وتعمل عل تقليل المفاقيد في الشبكات وتعزز من مستوي الجهود. ومع ذلك، هناك تحديات تواجه إدخال الوحدات الموزعة في نظم الطاقة مثل مشاكل منظومة الحماية الكهربية وانفصال جزء من المنظومة عن الشبكة الرئيسة (التجزر). وجرت العادة على اتخاذ احتياطات تقليدية بعد عملية التجزر وهي فصل هذه الوحدات لضمان التشغيل الأمن للشبكة. في هذه الحالة، تقل اعتمادية الشبكة وتصبح عملية اعادة التشغيل من الامور المعقدة. ولذلك، يُفضِل العديد من أصحاب الوحدات الموزعة السيطرة على عملية التجزر، وتحسين خرج الوحدات الموزعة لضمان تغذية الأحمال القريبة لهذه الوحدات. ومن هنا, ظهر مفهوم التجزر المتعمد والذي يعني فصل بعد الأجزاء من الشبكة مع ضمان تغذية الجزء الاكبر من الاحمال بها فيما يسمى بالجزيرة. ولكي تتم تلك العملية، لابد أن تكون منظومة التوزيع مزودة بنظم للرصد والمراقبة تساعد على الكشف عن حالة فقدان الاتصال بالشبكة الرئيسة أو تساعد مشغلي الشبكة على تكوين تشكيلات متعمدة للجزر.

تقدم هذه الدراسة منهجية جديدة للتعامل مع التجزر المتعمد لزيادة اعتمادية نظم التوزيع. وتستند هذه المنهجية على خوارزميات لفصل الأحمال الزائدة عن خرج المولدات لتحقيق توازن بين المولدات والأحمال. بالإضافة إلى ذلك، فان هذه الدراسة تقدم أيضا استراتيجية للسيطرة على الجهد والتردد لضمان الانتقال السلس من حالة الاتصال بالشبكة إلى وضع الجزيرة. ويمكن للخوارزميات تحسين اعتمادية نظام التوزيع ككل من خلال ضمان تغذية الأحمال الهامة وذات الاولوية حتى في حالات صيانة الشبكة بالإضافة إلى تقديم تحليل ديناميكي مفصل لشبكة التوزيع في حالة التجزر. وقد تمت هذه الدراسة الديناميكية في أسوأ ظروف التحميل وأثبتت النتائج نجاحها للانتقال إلى حالة عزل الجزيرة عن الشبكة. يمكن لنظام الرقابة المحلية (DCS) للجزيرة تعديل تردد المولد وأيضا جهده لضمان جودة الطاقة المُزودة للأحمال في كل نظام معزول جديد. بالإضافة إلى ذلك، لابد من تقييم الاستقرار في الجزر الجديدة لتقييم أدائها وإعطاء الأولوية ما بين البدائل المختلفة سواء كانت للجزر بذاتها أو مجموعات متآلفة منها.

تُقدم هذه الرسالة على هيئة خمسة فصول يمكن استعراض محتوياتها الأساسية فيما يلي:

المستخلص

تقدم هذه الرسالة طريقة جديدة للتعامل مع التجزر المتعمد وذلك لزيادة الاعتمادية لشبكات التوزيع. تعتمد هذه الطريقة بالأساس على اقتراح خوارزمية جديدة لفصل الاحمال لتحقيق الاتزان المنشود ما بين القدرة المُولدة والاحمال في نفس الجزيرة وأيضا تم تقديم طريقة للتحكم في خرج المولدات (الجهد والتردد) لكي توائم الحالة الجديدة. تتضمن هذه الرسالة أيضا دراسة الأداء الديناميكي المفصل للحظة الانتقال الي حالة التجزر المتعمد. وقد تم اختبار هذا الانتقال عند أقصى تحميل لكل جزيرة حيث اثبتت النتائج فعالية هذه الطريقة المقترحة. ويمكن تلخيص ما تم تقديمه في الرسالة فيما يلي:

أولا: الاختيار الأمثل لأماكن الوحدات الموزعة في الشبكة الكهربية.

ثانيا: اختيار تكوينات من الجزر وفقا للحد الأدنى من معدل فصل الأحمال.

ثالثا: اقتراح خوارزمية لفصل الأحمال في كل جزيرة بحيث لا يزيد معدل الفصل عن ٣٠% ويكون الفصل سريع لكي يناسب ان تعمل هذه الخوارزمية في حالات التشغيل الفعلي.

رابعا: رصد لحظات الانتقال العابر من النظام العادي إلى حالات التجزر.

خامساً: التحقق من جودة القدرة (الجهد والتردد) وتعديل التحكم في المولدات لتنظيم الجهد والتردد إذا لزم الأمر.

سادسا: التحقق من استقرار النظام المعزول الجديد (الجزيرة) عند زيادة الأحمال تدريجياً في الجزيرة.

وقد تم تطبيق هذه الخطوات بهدف زيادة اعتمادية أنظمة التوزيع والمحافظة على استمرار الخدمة للأحمال الهامة وخفض معدل المفاقيد في الطاقة خلال الشبكة.

الي ملهم هذا العمل الذي لم يقرأه أبدا....

لجنة الحكم والمناقشة لرسالة الماجستير المقدمة من

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بعنوان

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للحصول على درجة ماجستير العلوم في الهندسة
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سيناريوهات التجزر للتشغيل عالي الإعتمادية لشبكات التوزيع

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