LOAD SHEDDING SCHEME BASED ON FREQUENCY AND RANKED STABILITY INDEX CONSIDERING OPTIMAL SELECTIVITY OF LOAD IN ISLANDED DISTRIBUTION SYSTEM

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THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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LOAD SHEDDING SCHEME BASED ON FREQUENCY AND RANKED STABILITY INDEX CONSIDERING OPTIMAL SELECTIVITY OF LOAD IN ISLANDED DISTRIBUTION SYSTEM

ABSTRACT

The widespread use of renewable energy sources as Distributed Generations (DGs) in distribution system causes few technical concerns. One of the major concerns is the possibility of islanding occurrences, where the grid is disconnected from the distribution system. When islanding occurs, the system frequency and voltage are severely disturbed due to imbalance between power generation and load demands. Due to this, the DGs are required to be disconnected to avoid system instability and safety issues. However, in the long run, this action is not a wise approach since DGs may able to energize some of the loads in the system. In order to allow DGs to continue operating in islanding mode, imbalance between power generation and load demands must be addressed. One of the possible solutions is to apply load shedding scheme where some loads in the system are disconnected to balance the power between generation and load demands. This scheme has been widely applied in the transmission system, which proven able to stabilize the system frequency. However, islanded distribution network is not as stable as in transmission system that supported with many generations. Thus, a new load shedding scheme is required to ensure frequency and voltage is preserved when load shedding mode takes place.

Due to the importance of load shedding for the islanded distribution system, this research aims to propose a new load shedding scheme considering frequency and Voltage Stability (VS). To achieve this, VS index and optimal selectivity of load to be shed are incorporated in the proposed load shedding scheme. A ranking algorithm referred as Bus Ranked Voltage Stability (BR_{VS}) is proposed where the bus (according VS value) is sorted according to the stability value of the bus, from the weakest to the strongest. The weakest bus indicates the critical bus, which is near to collapse point in the system. Based on the BR_{VS}, the weakest bus is given priority to be shed during system disturbances. The proposed scheme also considered the optimal load to be shed based on the VS index and power imbalance criteria. In order to consider both criteria in a balance manner, Analytical Hierarchy Process (AHP) method is adopted.

The effectiveness of the proposed scheme is validated through simulation by using PSCAD/EMTDC software. An existing Malaysian network (25 bus system) interconnected with mini hydro generations is used for the test of the proposed scheme. The simulation results show that the proposed scheme managed to shed the optimal amount of load when compared to Conventional and Adaptive Under Frequency Load Shedding Scheme. Apart from frequency stability, the proposed scheme also shows significant improvement in the voltage profile in the islanded system. Moreover, it has been observed that the proposed scheme successfully improves the performance of voltage magnitude in more than 90% from all buses in the system.

Keywords: Under frequency load shedding, voltage stability index, islanding, distributed generation, load selectivity

LOAD SHEDDING SCHEME BASED ON FREQUENCY AND RANKED STABILITY INDEX CONSIDERING OPTIMAL SELECTIVITY OF LOAD IN ISLANDED DISTRIBUTION SYSTEM

ABSTRAK

Penggunaan meluas tenaga boleh diperbaharui sebagai generasi diedarkan (DGs) dalam sistem pengagihan menyebabkan beberapa kebimbangan teknikal. Salah satu daripada kebimbangan utama adalah kemungkinan kejadian islanding, di mana grid diputuskan dari sistem pengagihan. Apabila islanding berlaku, frekuensi sistem dan voltan adalah teruk terganggu disebabkan oleh ketidakseimbangan antara penjanaan kuasa dan beban permintaan. Oleh kerana ini, DGs hendaklah diputuskan untuk mengelakkan ketidakstabilan sistem dan isu-isu keselamatan. Walau bagaimanapun, dalam jangka masa panjang ini bukanlah satu pendekatan bijak kerana DGs mungkin dapat membekalkan beberapa beban pada sistem. Untuk membolehkan DGs untuk terus beroperasi dalam keadaan islanding, ketidakseimbangan antara penjanaan kuasa dan beban tuntutan mesti ditangani. Salah satu penyelesaian yang mungkin adalah untuk memohon skim beban menumpahkan. Skim ini telah digunakan secara meluas untuk sistem penghantaran, di mana beban pada beberapa bahagian sistem itu dikeluarkan untuk mengimbangi penjanaan dan beban permintaan untuk menstabilkan frekuensi sistem.

Walau bagaimanapun, rangkaian pengedaran islanding tidak stabil seperti dalam sistem grid. Oleh itu, satu skim beban menumpahkan baru diperlukan bagi memastikan frekuensi dan kestabilan voltan dipelihara apabila beban menumpahkan berlaku.Oleh kerana kepentingan beban menumpahkan untuk sistem pengagihan islanding, kajian ini bertujuan untuk mencadangkan satu skim baru, bagi mengambil kira sistem frekuensi dan voltan kestabilan. Untuk mencapai matlamat ini, kestabilan voltan indeks dan pemilihan optimum beban telah dicadangkan. Kedudukan bus indeks mengikut kestabilan (BR_{VS}) dicadangkan di mana bus (mengikut VS nilai) disusun mengikut yang paling lemah kepada kuat. Berdasarkan BR_{VS}, bus yang paling lemah adalah diberi keutamaan untuk dialihkan semasa gangguan. Skim yang dicadangkan juga bertujuan untuk menghasilkan keputusan yang optimum berdasarkan kriteria indeks VS dan ketidak seimbangan kuasa. Untuk mempertimbangkan kedua-dua kriteria, Analytical Hierarchy Process kaedah (AHP) diguna pakai. Kaedah ini akan memastikan kedua-dua kriteria dipertimbangkan secara bijak dan seimbang.

Keberkesanan skim yang dicadangkan itu disahkan melalui simulasi yang menggunakan perisian PSCAD/EMTDC. Rangkaian Malaysia sedia ada (25 sistem bas) dengan generasi mini hidro digunakan untuk menyuji skim yang dicadangkan. Keputusan simulasi menunjukkan bahawa skim yang dicadangkan berjaya menurunkan jumlah optimum beban berbanding UFLS konvensional dan penyesuaian. Selain kestabilan frekuensi, skim yang dicadangkan itu juga menunjukkan peningkatan yang ketara dalam profil voltan dalam sistem islanded. Lebih-lebih lagi, ia telah diperhatikan bahawa skim yang dicadangkan berjaya meningkatkan prestasi magnitud voltan dalam semua bas di dalam sistem.

Kata kunci: Di bawah beban frekuensi penumpahan, indeks kestabilan voltan, keadaan islanding, generasi yang diedarkan, selektiviti beban

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LIST OF SYMBOLS AND ABBREVIATIONS

AHP	:	Analytical Hierarchy Process
AHPM	:	Analytical Hierarchy Process Module
ANFIS	:	Adaptive Neuro Fuzzy Inference System
ANN	:	Artificial Neural Network
BR_{AHP}	:	Bus Ranked According Analytical Hierarchy Process
BR_{COM1}	:	Bus Ranked According COM1
BR_{COM2}	:	Bus Ranked According COM2
BR_{VS}	:	Bus Ranked According Voltage Stability
BR_{VS_LC}	:	Bus Ranked According Voltage Stability and Load Category
DGs	:	Distributed Generations
EOM	:	Event Operation Module
FLC	:	Fuzzy Logic Control
FVSI	:	Fast Voltage Stability Index
GA	:	Genetic Algorithms
LC	:	Load Category
LSCM	:	Load Shedding Controller Module
LSCCM	:	Load Shedding Controller Criteria Module
MELC	:	Minimum Error Load Combinations
MHSG	:	Mini Hydro Synchronous Generator
NVSI	:	New Voltage Stability Index
OCLEM	:	Optimal Error Least Error Module
OPF	:	Optimal Power Flow
PSCAD	:	Power Simulator Computer Aided Design
PSO	:	Particle Swarm Optimization

PTSI	:	Power Transfer Stability Index
PID	:	Proportional Integral Derivative
RE	:	Renewable Energy
RCB	:	Remote Circuit Breaker
ROCOF	:	Rate of Change of Frequency
SFM	:	System Frequency Module
SLCM	:	Stability and Load Category Module
UFLS	:	Under Frequency Load Shedding Scheme
$UFLS_{AHP}$	:	Under Frequency Load Shedding Scheme based on Analytical Hierarchy Process
$UFLS_{ADAP}$	:	Adaptive Under Frequency Load Shedding Scheme
$UFLS_{CONV}$	:	Conventional Under Frequency Load Shedding Scheme
$UFLS_{VS}$	:	Under Frequency Load Shedding Scheme based on Voltage Stability
$UFLS_{VS\_LC}$	:	Under Frequency Load Shedding Scheme based on Voltage Stability and Load Category
UVLS	:	Under Voltage Load Shedding Scheme

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CHAPTER 1: INTRODUCTION

1.1 Background of Research

The economic development and sustainability of any country around the world is measured by its energy production. Commonly, majority of the produced energy is from fossil fuels resources. According to the International Energy Agency ("International Energy Agency," 2016), the total energy consumption is mainly from fossil fuel which accounts for 78% whereby the crude oil consists of 39.3%, natural gas 15.1%, biofuels 12.2% and coal 11.4% in 2014. However, excessive use of conventional fossil fuels has resulted in climate changed due to greenhouse emissions, carbon emissions, sulphur dioxide and nitrogen dioxide emissions. Furthermore, it has been reported that the electrical power sectors resulted in one-third (1/3) of total world Green House Gases (GHG) emissions (Pan et al., 2013; Sheen et al., 2013; Yaniktepe et al., 2013). Due to environmental concerns, it is a critical objective for most countries to reduce carbon emissions for their social and economic development. Therefore, replacing the fossil fuels with Distributed Generations (DGs) based on renewable energy resources (Silva et al., 2012) can significantly reduce GHG emissions.

Over the last decades, the numbers of DGs that are being connected to a distribution grid has substantially increased to meet increased power demands. According to the IEEE standard 1547, a DG is an electric generation facility connected to a power system through a point of common coupling. The common RE sources used for DGs are based on wind, hydro, and photovoltaics. The integration of DGs resulted in environmental benefits, improvement in voltage profile and power quality in the system (Barker et al., 2000). Due to these advantages, the interconnection of DGs into distribution networks is undergoing a rapid global expansion. In fact, many power utility companies around the world have embarked on installing DGs within their distribution networks. The increasing number of

DGs in various countries is also due to the RE policies focusing on promoting environmental friendly energy sources. For example, the European Union had set a target to replace 20% of the electricity generated from fossil fuels with RE sources by 2020 (European Union Commission Report, 2005). In this regard, Malaysia has also set a target to utilize 6% RE by the end of 2015, and 11% by the end of 2020 (Hashim et al., 2011). Based on policies in RE utilization, the penetration of DGs in power system network is expected to continue increasing in the near future.

The high DGs penetration in distribution system could cause some technical concerns. One of the major concerns is the possibility of islanding occurrences. According to IEEE standard 1547, DGs are required to be disconnected during the islanding event to avoid system instability. However, this practice is uneconomical, since DGs could be used to energize some of the loads in the islanded system. Similarly, the benefit of DGs will not fully be explored if the DGs are tripped off whenever there are system disturbances in the grid side. With the high penetration of DGs expected in the near future, this tripping scenario is inappropriate and causes further inconvenience for customers. Hence, the intentional islanding operation with proper control can be a feasible option to allow DGs to operate during islanding mode. The DG must be able to assume the role of grid independently by supplying the whole island. Various research have been conducted, and are on-going, all of which intending to make the islanding operation a reality (Atwa et al., 2009; Balaguer et al., 2011a; El-Arroudi et al., 2007; H. Karimi et al., 2008; Lopes et al., 2006). From the past research, it can be observed that several researches take considerations for the successful of operation of DG in islanded distribution system**.**

1.2 Problem Statement

In order to ensure successful islanding operation, the crucial matters involved are to control the frequency and voltage within the allowable limits. The frequency and voltage are severely disturbed due to power imbalance between power generation and load demand. The frequency will rapidly decrease due to excess in load demand in the islanded distribution system. Meanwhile, the bus voltage magnitude also experiences drop at the areas furthest away from the DGs. DGs with small system inertia can cause the rapid frequency decline in the system. Additionally, the limitation of DG spinning reserve may cause huge power imbalance in the islanded system. Furthermore, if the DG reaches reactive power limits, it will cause rapid voltage drop. This situation can lead to DG tripping and finally cause the islanded network to experience total blackout. Hence, the islanding operation of a distribution network may be a viable option, provided that various issues related to it are properly addressed.

When a distribution system is disconnected from the grid, some loads may need to be shed in order to stabilize the system frequency and voltage. Realizing on this importance, many researches have been done for load shedding scheme. Generally, the load shedding scheme can be categorized as either Under Frequency Load Shedding (UFLS) or Under Voltage Load Shedding Scheme (UVLS) (Saffarian et al., 2011). Commonly, these load shedding schemes are designed independently in the power system. For example, as reported in (Pasand et al., 2007; V. Terzija et al., 2002b; V. V. Terzija, 2006a), the UFLS is proposed to estimate the power imbalance, while the optimal UFLS is proposed in (Hooshmand et al., 2012). For UVLS, various research as undertaken to prevent voltage instability (Adewole et al., 2016; Amraee et al., 2011; Arief et al., 2013; Mahari et al., 2016). Most of these works are focused on addressing voltage instability in transmission systems and very limited work for distribution system. Even though past researches have been proposed the load shedding in islanded distribution system (Gu et al., 2013; M. Karimi et al., 2012; Ketabi et al., 2014; J. Laghari et al., 2015; Mahat et al., 2010b; Mokari-Bolhasan et al., 2014; Rudez et al., 2011a), these studies only highlights system frequency as the main factor in the determining load shed.

Other studies have considered Voltage Stability (VS) in the load shedding for transmission line (Arya et al., 2005; Echavarren et al., 2006; El-Sadek et al., 1999; Kanimozhi et al., 2014; Nizam et al., 2007; Sadati et al., 2009; Sasikala et al., 2011). It can also be observed that load shedding scheme is designed based on either frequency or VS. Since UFLS takes into account only the system frequency as the main criterion for load shedding, it may contribute to unanticipated or adverse consequences of system voltage. On the other hand, load shedding scheme based on VS alone may also affect the frequency stability. There has been no attempt to integrate frequency and VS in load shedding scheme for an islanded distribution system. There are some research works which have considered frequency and VS in load shedding scheme (Tang et al., 2013b), but the proposed work is for a transmission system only. Considering the needs of ensuring both frequency and VS for load shedding, this research proposes an UFLS that considers frequency and VS simultaneously for load shedding in the islanded distribution system.

Currently, the researches proposed the VS index for distribution system have been reported in (Eminoglu et al., 2007; Kumaraswamy et al., 2016; Mahmoud, 2012; Murthy et al., 2014; Pujara et al., 2011). In (Mahmoud, 2012; Pujara et al., 2011) uses the voltage stability index to identify the most sensitive bus in the radial distribution network. Meanwhile, the Stability Index (SI) index based on transferred active and reactive power is used to recognize the critical bus in the radial distribution line (Eminoglu et al., 2007). The SI index is analysed to determine the most critical bus as presented in (Yamuna.P et al., 2015). Also, study has also been carried to analyse the integration of VS index to determine the optimal location for DGs in distribution system in (Kumaraswamy et al., 2016; Murthy et al., 2014). Although these works can determine the critical buses in the distribution system, they have certain limitations. These works did not include the load shedding and the proposed scheme is not for islanded system. Also, the analysis on VS index does not explore with different type of VS indices in order to identify the most appropriate index that suitable for distribution system. The VS index that suitable for transmission system may not suitable for distribution system due to radiality structure and high R/X ratio. The appropriate VS index can be applied for proposed load shedding scheme considering frequency and VS in islanded distribution system. Research in (N. A. Yusof et al., 2017) highlights the analysis for different type of VS in islanded distribution system, however the frequency is not considered.

Following system islanding, the frequency will decline if the load demands are more than the total generation. Hence, an efficient load shedding technique is required to shed optimal amount of load in order to stabilize the frequency. Improper load shedding may lead to power blackout. This occurred in United States and Canada on 14th August 2003. This blackout affected around 50 million people in eight US states and two Canadian provinces. Estimates show that this blackout interrupted around 63 GW of load, and more than 400 transmission lines and 531 generating units at 261 power plants tripped (Chang et al., 2011; Pourbeik et al., 2006; Zhao et al., 2009). Hence, the optimal load shedding is crucial to avoid blackout events in the system. The optimal load shedding scheme can be determined based on accurate power imbalance estimation and the selectivity of load to be shed following system disturbances. Most research focus to obtain optimal load to be shed from accurate power imbalance estimation (M. Karimi et al., 2012; V. V. Terzija, 2006a). Currently, research regarding the selectivity of load to shed is not considered. This issue is very important and needs to be considered. In previous research, the selection load to shed is considered either based on active power load criteria (M. Karimi et al., 2012) or based on VS value criteria (N. A. Yusof et al., 2017). Both criteria are not considered simultaneously in the load shedding process. Although research in (J. Laghari et al., 2015) proposed the optimal load shed based on the least error of power from load combination, this work did not consider the VS criteria in the proposed scheme. Hence, decision-making technique is required in order to consider both, active power load criteria and VS index criteria in a balance way for optimal selectivity of load shedding.

1.3 Research Objectives

This research mainly focuses to produce an effective of load shedding scheme for islanded distribution system. The following are the objectives to achieve the aim of this research:

1) To propose a new load shedding scheme based on a combination of system frequency and voltage stability index.
2) To analyse the performance of seven voltage stability indices in the proposed load shedding scheme.
3) To formulate optimal load selectivity based on minimum error of power-load balance.
4) To incorporate Analytical Hierarchy Process method in the proposed load shedding scheme using suitable voltage stability index for enhancement of load selectivity.

1.4 Scope of Research

The scopes of this research are as follows:

1) This research only considers two major technical issues consisting new load shedding scheme based on system frequency and Voltage Stability (VS) and the load selectivity for load shedding using decision making Analytical Hierarchy Process (AHP) method.
2) The proposed scheme is tested on the existing Malaysia's distribution network consisting of two small mini hydro generations which uses rotating type DG which are synchronous generator and induction generator. The load is categorized into three types; vital, semi-vital and non-vital. These categories are based on the importance of load.
3) In this research, the islanding detection is assumed to be available to trigger the proposed load shedding scheme.
4) In the simulation, the power system components are modelled in PSCAD/EMTDC software. Standard power system models in PSCAD/EMTDC software have been used. New components are also developed for some of the non-available models mainly the proposed UFLS scheme. The necessary modules are developed with the PSCAD script using FORTRAN programming language.
5) In order to ensure the success of the proposed load shedding scheme, all measurement units are provided in the test system. The communication links are also assumed available in the test system to ensure that the signal is fast enough to respond to any disturbance in the system.

1.5 Research Methodology

In order to achieve the objectives, following research methodology will be carried out:

1) The background of distribution networks, DG based on synchronous generators, UFLS scheme, and Voltage Stability (VS) will be studied.
2) An appropriate VS index which is applicable for distribution network is analysed based on literature review.
3) The UFLS scheme which incorporates VS index ranking is selected as the proposed method.
4) Validation of the proposed technique in distribution network will be carried out using PSCAD/EMTDC software.
5) Designing the UFLS where the decision making will be based on combination of stability criteria and load category criteria.
6) Compare the performance of the proposed UFLS against the conventional and adaptive schemes.

1.6 Thesis Outline

This thesis consists of seven chapters and three appendices which are organized as follows:

Chapter 1 presents the motivation of this study in developing a new load shedding scheme for islanded distribution system. The objectives of this study followed by scope of the research are also discussed. In the end, research methodology and thesis outline are presented.

Chapter 2 focuses on the integration of DGs in the distribution system and its benefits. The islanding phenomenon with their technical issues which restricts its implementation in distribution network is presented. It also includes the unintentional and intentional islanding and their related issues. The current practice of islanding is also discussed followed by methods and requirements to continue islanding operation. In the end, comparative analysis on UFLS techniques is reviewed. Also, the load shedding scheme based on Voltage Stability (VS) index is also reviewed in this chapter.

Chapter 3 presents the fundamental concept and methodology of proposed load shedding scheme based on frequency and VS. In this chapter, two approaches of load shedding schemes are presented. In the first approach, the UFLS based on VS index ranked is proposed. The description of the module used in this proposed scheme is also presented. In the second approach, the UFLS based on VS index ranked and Load Category (LC) is presented.

Chapter 4 deals with the fundamental concept and methodology of the proposed load shedding scheme considering optimal load selectivity using decision making technique. The description of AHP method for decision making is presented. The proposed module to obtain set of load combination with least error between power generation and load demand is also discussed in this chapter. The methodology of the proposed algorithm based on AHP method for load shedding is also presented. Finally, the proposed of load shedding controller based on AHP method for load selectivity is shown.

Chapter 5 presents the simulation results of the proposed load shedding scheme under islanding and sudden load increment cases. In the beginning of this chapter, the modelling of the 25-bus distribution system for the validation of the proposed load shedding scheme is presented. Then, the results of the proposed load shedding scheme with both approaches is discussed. The proposed load shedding scheme is compared with the conventional and adaptive load shedding scheme. The simulations result presents the frequency and voltage performance of the system network for light and peak load conditions for all VS index.

The analysis for VS index is also presented in this chapter. This chapter proves that the proposed load shedding scheme provides better performance of system frequency and improved voltage magnitude.

Chapter 6 presents the simulation results for the load shedding based on the load selectivity using AHP method. The best two combinations of loads with least error combination are selected through the proposed algorithm. This chapter also presents the weight analysis for each alternative and weight for criteria in the VS index. The proposed load shedding scheme is compared with the conventional, adaptive, and UFLS scheme based on VS and LC. The simulation result presents the frequency and voltage performance of the system for peak load conditions. This chapter proves that the proposed load shedding based of AHP load selectivity provides better performance in terms of voltage magnitude as well as the frequency response.

Chapter 7 concludes this thesis by summarizing the research contribution and presents possible future work for this research.

Appendix A presents the test system modelled in PSCAD/EMTDC software. It also presents the modules of proposed load shedding scheme designed in PSCAD software. These modules have been developed with PSCAD script through FORTRAN programming language.

Appendix B presents the analysis for all VS index based on the simulation results.

Appendix C presents the analysis for all possibilities of load combination from the proposed Optimal Combination of Least Error Module (OCLEM). The least error value for each combination is analysed in this section.

Appendix D presents the weight analysis based on AHP for all indices.

CHAPTER 2: APPLICATIONS OF LOAD SHEDDING SCHEME FOR ISLANDED DISTRIBUTION NETWORK: A REVIEW

2.1 Introduction

In the recent years, Distributed Generation (DG) are being widely used in the distribution system to meet increased load demand. This chapter begins with an overview of DG, followed by their benefits, and integration in the distribution system. The phenomenon of islanding will be discussed with their issues and technical difficulties which restrict its operation in islanding mode. The proper solution of these issues that can make islanding a feasible solution will also be discussed. Moreover, this chapter provides the background and current research related to load shedding schemes in order to make islanding operation successful.

2.2 Distributed Generation Penetration in Distribution System

The exponential growth in electricity demand has driven the DG technology a boost in the power system. DG is predicted to play crucial role in electric power system in order to sustain the load demand. According to ("IEEE Std 1547," 2003), a DG is an electric generation facility connected to power system through a point of common coupling. A DG is available in different sources which provide the customers wide range of cost and reliability. Moreover, the DG has been widely employed as an alternative option for electric power generation. This results in the enhancement of energy efficiencies, improvement in voltage profile and power quality. In fact, many power utilities around the world already have significant penetration of DG in their distribution networks.

Despite of many advantages, the increasing trend of DG penetration in power system network requires system configuration to be changed. In this regard, several standards have been adopted in order to fully utilize the RE to meet the customer demand as given below:

1) IEEE Standard for Interconnecting Distributed Resources with Electric Power System (IEEE Std1547,2003)
2) IEEE Recommended Practice for Utility Interface of Photovoltaic (RAJ et al.) System (IEEE Std929,2000)
3) IEEE Guide for Protective Relaying of Utility-Consumer Interconnections (IEEE StdC37.95,2014)

2.3 Benefits of Distributed Generations

The generation sources from RE can significantly impact to the power and voltage flow either at consumer or utility side. This scenario can cause negative or positive impact to the system operation depending on the system planning and operation. The positive impacts are generally called "system support benefits" (Barker et al., 2000). Figure 2.1 summarized the benefit of DG (Badran et al., 2017; Theo et al., 2017).

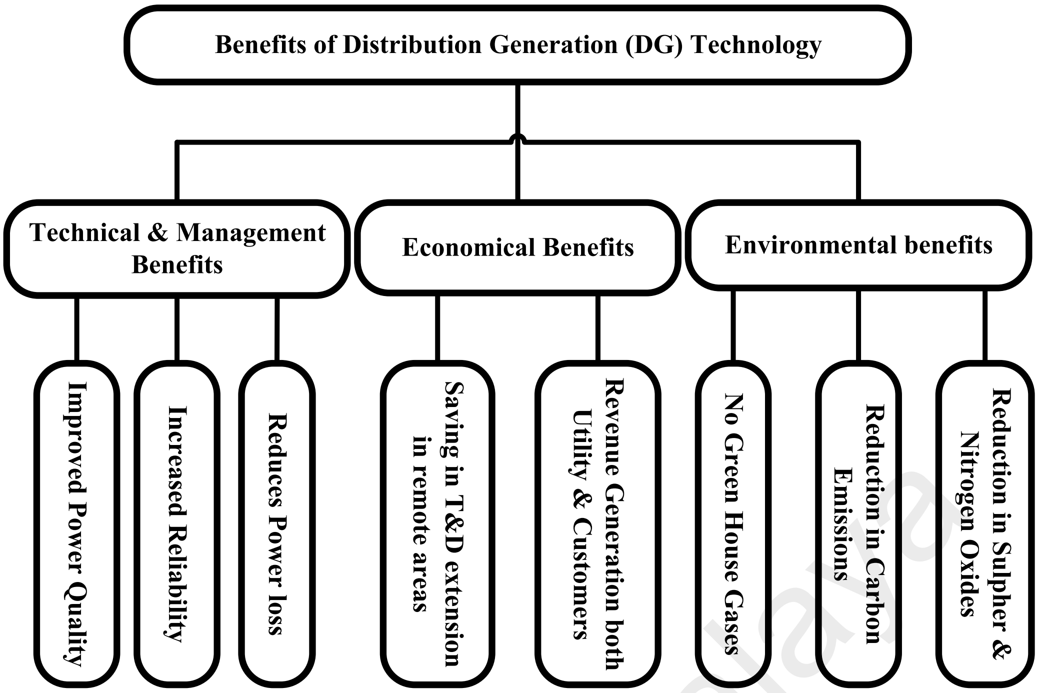


Figure 2.1: Benefits of distributed generation

In order to achieve these benefits, the DG sources in practice should be reliable and able to meet various operating criteria either steady state or dynamic condition. Since DG itself not only owned by the utility, the introducing of RE sources should be satisfied to fully utilize the generation to meet customer demand. The increasing of RE generation recently, look as an alternative to safe the environmental problem and reduce the cost of power plant construction (Jang et al., 2004). Thus, the DG must operate with the proper control and protection strategy integrated with the grid system. Furthermore, the penetration of DG in power system causes certain technical issues, which are the main barriers in the development of DG in the power system. Figure 2.2 summarizes these barriers.

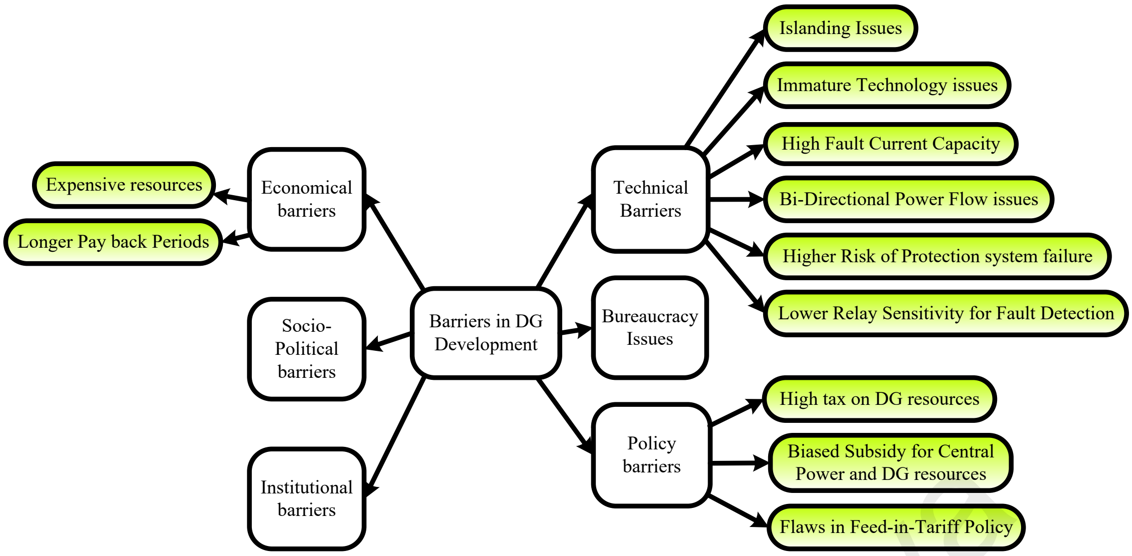


Figure 2.2: Barriers in distributed generation development

Among these barriers, the islanding issue is one concern for practical implementation in the power system network.

2.4 Islanding Operation in Distribution System

In general, DG can be operated either in grid connected mode or islanding mode. The DG should be feasible in safety manner to feed the load demand during system disturbances. Due to sudden serious hazardous happen in the system, such as sudden outage of large generating unit or sudden outage of transmission line (Rudez et al., 2011a), the DG is required to be disconnect from the grid as soon as possible, and operated in the islanded mode operation (Hashim et al., 2011).

Figure 2.3 illustrates the islanding operation in the distribution system. In the event of islanding, DG becomes electrically isolated from the remainder of the power system, yet continues to be energized by the DGs connected to it.

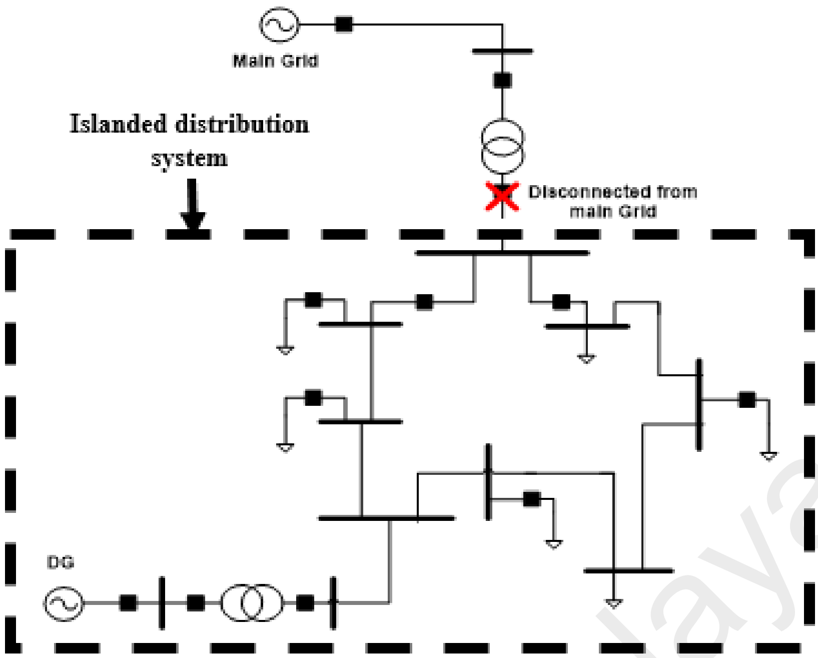


Figure 2.3: Islanded distribution system

Following system islanding, the distribution network is disconnected from the main grid through circuit breaker operation. In other words, the system is lost some portion of generation. Thus, create a power imbalance between power generation and load demand. The imbalance of power generated during islanded caused the frequency decline in the system. In case of small power imbalance, the turbine governor has enough time to control the frequency decay rate in contrast with the large imbalance. During large amount of power imbalance in the system, the mechanical turbine produced slow response to cater the further declining of system frequency. Due to this, the frequency may drop below its nominal value, causing heavy stress which may lead to overloading of the system or finally to blackouts.

As part of some consequences that islanding can bring, it is essential to control and restore the system frequency and voltage as quickly as possible to their nominal values. In general, the occurrence of islanding event can be classified as un-intentional or intentional. The description of both types is discussed in the following sections.

2.5 Un-intentional Islanding Operation and its Issues

The unintentional islanding operation of distribution network may occur due to sudden power system imbalance consisting of severe fault, line and generator outages that may result in splitting of the system into some islanded networks (Dola et al., 2006). In such case, the DG unit unintentionally may continue to energize the islanding area during grid disconnection (Mohamad et al., 2011). During these unintentional islanding conditions, the active and reactive power deficiency might occur, which may lead to frequency, angle and voltage instability. These instabilities condition may further cause tripping of other regions if not controlled properly. Consequently, the distribution system can expose to risk and hazard during large power mismatches to existing equipment, utility liability concerns, and the reduction of power reliability and power quality. Figure 2.4 shows the technical issues of islanding which are discussed in the following section (Mohamad et al., 2011):

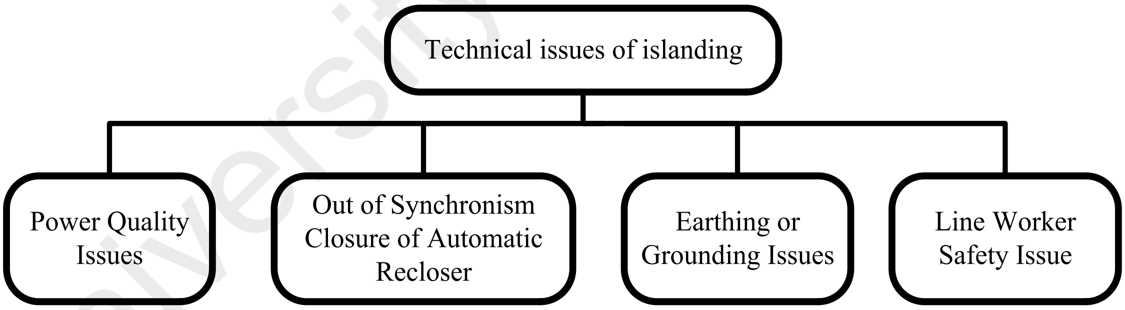


Figure 2.4: Main issues of unintentional islanding

2.5.1 Power Quality Issues

In the power system, the frequency and voltage are the important elements in order to maintain the continuity of power generation. However, during an unintentional islanding, the frequency and voltage can drop rapidly in case of large power imbalance between generation and load demand. Hence, it is essential to control and restore the frequency and voltage in the islanded distribution network as quickly as possible. Controlling the frequency and voltage within the permissible limit during islanding is the most important technical challenge being investigated worldwide.

2.5.2 Out of Synchronism Closure of Automatic Recloser

The auto-recloser equipped in the distribution substation is one of the important protective equipment. Due to formation of islanding, the auto-recloser will make several attempts to reconnect the island with the grid. This condition may lead out of synchronism of system phase angle, voltage magnitude and frequency during system reconnection. This condition has great potential to damage the prime mover of the generator DG unit due to large mechanical torque and currents (M. Karimi et al., 2012; Walling et al., 2002). Meanwhile, the out of phase condition can damage the utility as well as customer equipment. The out of phase reclosing condition also can generate severe capacitive switching transient (Walling et al., 2002).

2.5.3 Earthing or Grounding Issues

Earthing or grounding issues also contribute to the safety of the system operation. In the power utilities, normally the single point earthing is adopted to be installed where the earth connection is located at the grid side. This condition is more beneficial in case where there is no DG present in the distribution system. However, in the presence of DG, a separate earthing is required at DG side to ensure the safe operation. As reported in IEEE Standard 142-2007, the DG required its own earthing system in islanded mode.

2.5.4 Line Worker Safety Issues

The risk of life for the line worker is another important issue to be solved in case for islanding operation. During system islanded, the islanded section might be energized by

DG. This situation may be threatened the line worker safety when working for maintenance purpose. This may happen due to unaware of the system condition. This can result in high risk if they still continue the maintenance works. To avoid this, it is required to increase the awareness and information among the safety line workers according the islanded system operation. In addition, the risk can be prevented with the proper operation manual.

2.6 Current Practice on Islanding

Presently, the islanding operation is prohibited due to above mentioned hazards and risk to the system in islanding mode as mentioned in (Ahmad et al., 2011), which states that the DG is not permitted to energize the island area for un-intentional islanding operation. Furthermore, the ("IEEE Std 1547," 2003) has put a regulation in case of such situation, the DG should detect the loss of grid connection and disconnect itself from the distribution network within 2s (100 cycles). In addition, some utilities require even fast detection time of less than 1s to avoid starting of auto-recloser attempt of reconnection. This is implemented in Danish distribution network, where the auto-recloser time is 500ms (Mahat et al., 2009). This time depend upon the protection coordination reclosing time of reclosers. However, it is also expected that due to high DG penetration, this practice may prove uneconomical. Hence, the intentional islanding operation of distribution network may be an option to avoid these issues provided that various issues related to it are properly addressed.

2.7 Intentional Islanding

Intentional islanding is the process of intentionally splitting the grid into the separate controllable islands (Pahwa et al., 2013). In such situation, the island region should have sufficient amount of power generation to supply the total load demand. It may be noted that intentional islanding is currently prohibited, there have been research efforts in intentional islanding operation. Various counties have installed microgrid system to evaluate the islanding effects and their respective solution (Bacelar et al., 2013; Balaguer et al., 2011b). Furthermore, several studies for feasibility of intentional islanding have been reported from different countries such as United Kingdom, Carolina, Thailand, India, Colombia, Brazil and Denmark. Thus, it can be concluded that the operation of DGs in the islanding mode has a potential to bring many benefits to the distributed generator owner and customer subjected to the condition that its issues are resolved properly.

2.8 Power System Stability

The successful islanding operation of the distribution network is closely related to the power system stability. Due to this, this section briefly discuses some background of power system stability. In power system, the frequency and voltage are essential elements to maintain the stability of the system. Power system stability is acknowledged as a crucial feature since the 1920s, especially in the context of securing system operation (Kundur et al., 2003). The stability of power system network can be defined as " *The ability of power system return to its nominal or stable operation after having been subjected to some form of disturbances*" (D P Kothari 2003). Conjunction with the increasing number of DG, maintaining the synchronisation of the system after being subjected to fault becoming more complicated.

For this reason, various emergency controls are necessary to ensure a safe and reliable operation of power system and avoid system blackouts. Generally, system blackouts occurred due to different forms of instability, either frequency instability or voltage instability (Mahari et al., 2016), or a combination of both (Saffarian et al., 2011). Power system stability can be classified into 3 main groups, which are rotor angle stability, frequency stability, and voltage stability (Kundur et al., 2003). The respective descriptions are subsequently discussed in Table 2.1.

Table 2.1: Classification of power system stability (Kundur et al., 2003)

Type of stability	Descriptions
Rotor angle stability	• Rotor angle stability refers to the ability to maintain the angular separation between synchronous machine units in the system due to the changes in the active power flow (Vittal et al., 2012). • The rotor instability phenomenon, generally associated with changes to active power flows that create angular separations between synchronous units in the system.
Frequency stability	• Frequency stability in power system can be defined as "The ability of the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load". • The frequency stability problems are associated with significant loss to generation in the islanded system, inadequacies in equipment response, poor coordination of control and protection equipment, and insufficient generation reserve.
Voltage stability	• Voltage stability can be defined as "The ability of power system to maintain acceptance voltage at all buses in the system under normal condition and after being subjected to disturbances". • The possible outcome for voltage instability is loss of load in certain area, tripping of transmission line and loss of synchronism of some generators.

Table 2.2 present several cases of short term and long-term disturbances in the world which have been reported in the past. From these cases, the different time scale of disturbances occurs for each case. Hence, in order to save the power system operation, the system should be able to maintain the system frequency and voltage within the normal value. Moreover, an efficient of system protection is required to response any form of disturbances in the system and able to bring to its normal value after being subjected to

disturbances. Thus, the load shedding technique is adopted in order to avoid instabilities condition following system disturbances.

Table 2.2: Cases of disturbance (D P Kothari 2003)

Disturbance	Date	Duration
South Florida, USA	May 17, 1985	transient, 4 secs
French	December 19, 1978 and January 12, 1987	longer term
Swedish	December 27, 1983	longer term, 55secs
Japanese (Tokyo)	July 23, 1987	longer term, 20min
Belgium	Aug 4, 1982	Longer term, 4.5min
Baltimore, Washington DC, USA	July 5, 1990	longer term, insecure for hours

2.9 Overview of Load Shedding Techniques

In order to ensure the stability of the power system, the frequency and voltage magnitude of the system must be monitored and controlled to ensure its value within the allowable limit. Both of these parameters (voltage and frequency) are not allowed to deviate much from its nominal value during steady state and disturbance condition. Otherwise, instability conditions might occur in the system that may lead to blackout. One of the major causes of frequency and voltage instability is due to imbalance between generated power and load demands. In the case where power generation unable to cope with load demands during operation, the last resort is to apply load shedding by removing some of the load from the system until balance between generation and load demands is achieved. Ineffective load shedding could lead to a high number of loads being shed or may lead to total power collapse. Therefore, effective load shedding scheme is needed to disconnect suitable amount of load and avoid power system from total system collapse. Load shedding scheme should be simple, efficient, and decisive (Concordia et al., 1995). Table 2.3 summarized some guidelines and factors that must be taken into account when dealing with a successful load shedding operation.

Table 2.3: Factors for the successful Operations of load shedding Schemes
(Ahmadi et al., 2015; Concordia et al., 1995; Delfino et al., 2001; Lokay et al., 1968a; Zin, Hafiz, & Aziz, 2004)

Factors	Descriptions
Minimum allowable system frequency	• Minimum of frequency operation value should be defined. The equipment does not operate below the acceptable frequency. • The equipment such as generators and steam turbine have their own limitation to withstand with frequency drops. This equipment is very sensitive with frequency decreased.
Correct amount of load to be shed	• It is required to determine the appropriate imbalance value between power generation and load demand to avoid the over shedding/under shedding in the system. • The amount of load shed should be determined by using the time simulation analysis considering dynamic aspects in power system.
Frequency threshold and time delay	• The time delay should take into account the short time of transient frequency and the steps of load shedding. • The action has to be quick, so that the frequency drop can be halted before the severe faults happen.
Location and selection for load shed	• Steam generation has priority over the electrical system and should be shed as soon as possible. • The important load such as hospital, should be avoided to be shed during system disturbances.
The timing and step size of load shedding	• In order to prevent unnecessary tripping during the transient time where load shedding is not required, the lowest time delay before the load shed is activated should be enough to prevent voltage failure. • The main reason for delaying load shedding is to make sure that the system is definitely in instable condition, hence avoiding load shedding excessively and the optimum of load shed amount.

In general, the load shedding scheme can be categorized into Under Frequency Load Shedding (UFLS) and Under Voltage Load Shedding (UVLS) schemes:

1) Under Frequency Load Shedding (UFLS) Scheme

In this scheme, the load shedding is initiated according to the system frequency changes. UFLS scheme ensures system frequency recovery to nominal value after being subjected to disturbance in the system that leads to imbalance power. For a small imbalance, the spinning reserve of the generator may able to address the small imbalance by generating the power from its extra generation capacity (Mokari-Bolhasan et al., 2014). However, in case spinning reserve responses are not fast enough to inject power, or the generator capacity already maximum, UFLS scheme need to be applied to restore the frequency. According to (Badran et al., 2017), UFLS is applied to restore the system frequency to a satisfying level following a considerable system emergency that can cause a generation failure and prevent a total system collapse, as well as help achieve fast restoration of all affected loads.

2) Under Voltage Load Shedding (UVLS) Scheme

In this scheme, the load shedding is initiated when the voltage drops to a certain level following system disturbance. In this case, the UVLS scheme is applied to recover the system voltage to acceptable level, thereby avoiding the more widespread voltage collapse. Voltage collapse refers to the condition where the voltage is suffering from lower voltage profile in some part of a power system.

In the past, several load shedding techniques have been proposed. Figure 2.5 illustrates the main types of load shedding schemes (J. Laghari et al., 2015; Mokari-Bolhasan et al., 2014; Rudez et al., 2011a). The following section provides detailed review of various load shedding schemes.

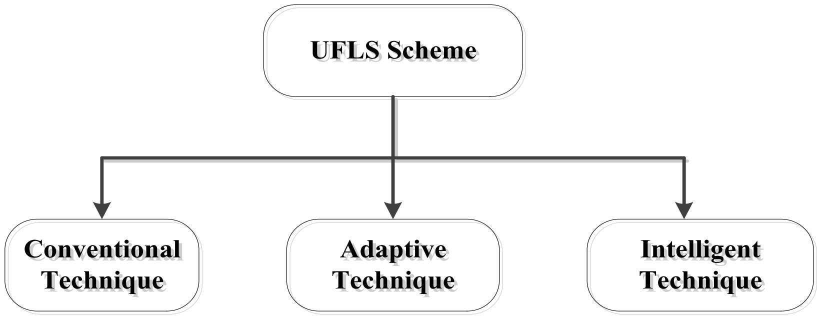


Figure 2.5: Under frequency load shedding techniques

2.10 Under Frequency Load Shedding (UFLS) Techniques: A Review

In this section, several UFLS techniques are reviewed with their merits and demerits. UFLS schemes are mainly classified in three categories such as conventional UFLS schemes, adaptive UFLS schemes and intelligent UFLS schemes.

2.10.1 Conventional UFLS technique

In early 1967, UFLS relays scheme was introduced to improve the deficit of generation in the system (Lokay et al., 1968b). From this scheme, several factors involved to achieve optimum relay settings were investigated. Initially, the rate of frequency decay is determined resulting from the amount of overload value. Then, the amount of load shedding required is specified based on the permissible frequency threshold value. The trial and error procedure are used to develop the number and size of load shedding steps to shed suitable amount of load.

UFLS relays however fail to achieve the optimal load shedding scheme since it shed the fixed amount of load at certain frequency thresholds (M. Karimi et al., 2012; J. Laghari et al., 2015). This scheme is widely known as the unreliable in shedding the right amount of loads (V. Terzija et al., 2002a; Xu et al., 2001) and can cause the frequency overshoot (Shokooh et al., 2005). Figure 2.6 shows the flow chart of conventional load shedding scheme.

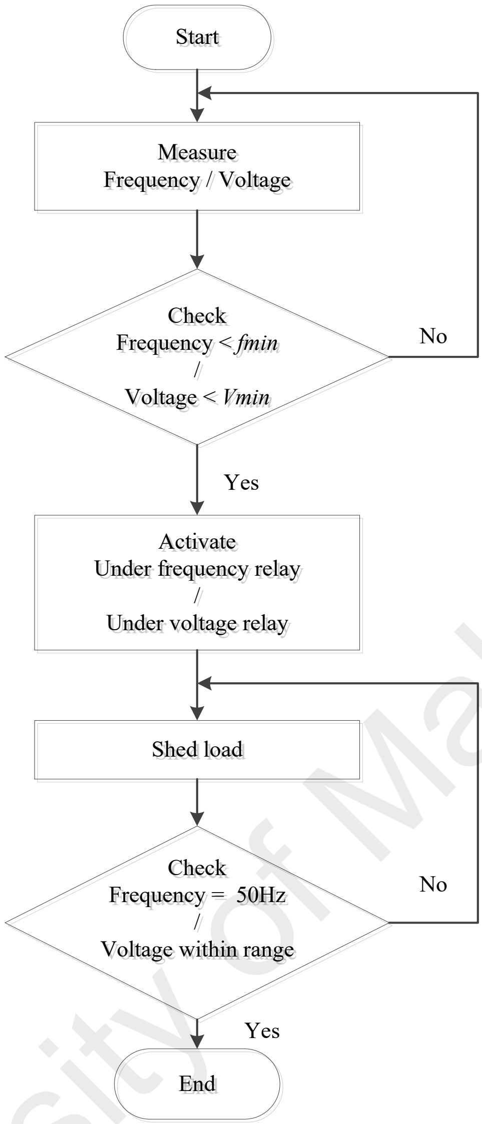


Figure 2.6: Flow chart of conventional load shedding scheme

The conventional scheme is initiated to shed a certain amount of load when the frequency falls at certain value. In the shortcoming events with large power overload, the relay setting fails to provide the load shedding procedure. An examples of this conventional UFLS is reported in (Zin, Hafiz, & Aziz, 2004), three different conventional UFLS have been implemented in Malaysian system network consists of 15-stage load shedding scheme.

Another important issue associated with conventional scheme is to determine the correct amount of power imbalance following disturbance. Commonly, the fixed amount of loads are shed at fixed frequency thresholds such as those reported in (Delfino et al., 2001; Junjie et al., 2013; Ketabi et al., 2014; V. V. Terzija, 2006a, 2006b). Consequently, the amount of load shedding may be higher or lower than what is required by the system in order to maintain the frequency and voltage within the permissible limits. This situation may lead to undesired damages of equipment and serious costs imposed to the system and load. Moreover, this technique provides the lack of flexibility to counteract for different types of instabilities (frequency instabilities and voltage instabilities) (Junjie et al., 2013; Rudez et al., 2011a). Due to the increasing number of modern power system operations, an efficient load shedding scheme capable of maintaining frequencies and voltage stabilities is duly required (Tang et al., 2013a). Thus, to improve its performance, the adaptive UFLS scheme has been proposed.

2.10.2 Adaptive UFLS Technique

The adaptive load shedding technique is proposed to improve the power imbalance estimation and to determine an appropriate location of load to shed which are unresolved efficiently from conventional techniques. An adaptive UFLS has been developed using the rate of change of the frequency (*df/dt*) to determine the magnitude of disturbance in the system (M. Karimi et al., 2012; Seyedi et al., 2009; V. V. Terzija, 2006a). It measures the ROCOF in the system, after which it estimates the disturbance magnitude of the power imbalance in the system. The simplest expression of the generator swing equation in (2.1) is adopted where H is the generator inertia constant (s), f_c is the frequency (Hz), f_n is the rated value of frequency (Hz), df_c/dt is the ROCOF (Hz/s), P_m is mechanical power in per unit and P_e is electrical power in per unit. It is possible to anticipate the power imbalance proportional to the system inertia constant. Two centralized adaptive algorithms (response based strategy, combination of response based and event based strategy) have been proposed in (Pasand et al., 2007; Seyedi et al., 2009).

$$\Delta P = \frac{(2 \times H)}{f_n} \times \frac{df_c}{dt} = P_m - P_e \quad (2.1)$$

In case for multi machine system generation, the generators will disturb with the inter generator oscillation during system disturbances causing the different oscillation among the generators. Apart from this, the equivalent value of Centre of Inertia Frequency (COIF) is introduced in equation (2.2) to estimate the equivalent of *COIF* for different rating of generators. Thus, the power imbalance value is estimated by using the expression in equation (2.3) (Rudez et al., 2011b; V. V. Terzija, 2006a; You et al., 2003):

$$f_{COI} = \frac{\sum_{i=1}^{N} H_i \times f_i}{\sum_{i=1}^{N} H_i} \quad (2.2)$$

$$\Delta P = ((2 \times \sum_{i=1}^{N} H_i / f_n) \times df_{COI} / dt) \quad (2.3)$$

Where ΔP is power imbalance, H_i is the inertia constant of i^{th} generators (s), f_n is the rated frequency (Hz), df_{COI}/dt is the rate of change of inertia frequency (Hz/s), f_{COI} is the frequency of centre of inertia (Hz) and f_i is frequency of i^{th} generator (Hz). The flow chart of adaptive load shedding scheme is shown in Figure 2.7 as reported in (Zin, Hafiz, & Aziz, 2004; Zin, Hafiz, & Wong, 2004).

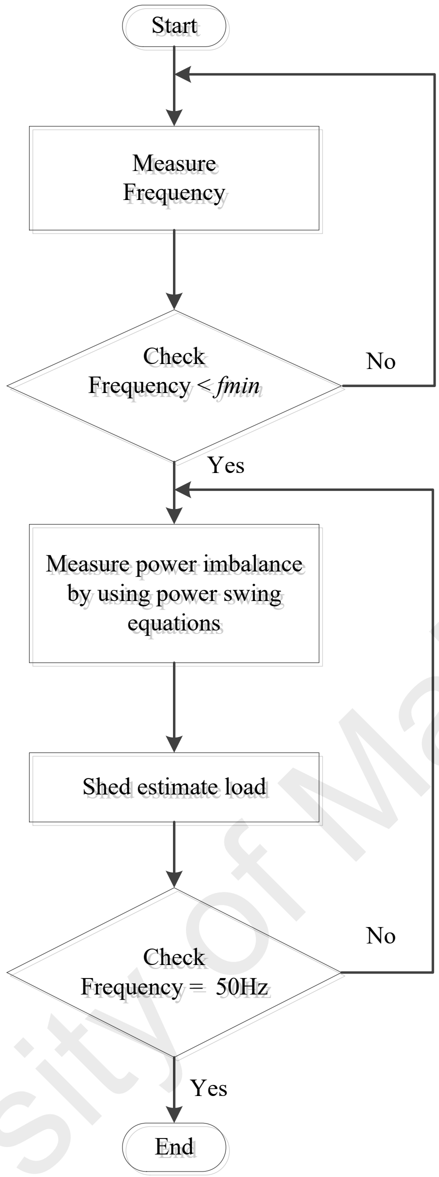


Figure 2.7: Flow chart of adaptive load shedding scheme

The author in (Delfino et al., 2001; Rudez et al., 2011b) proposed to distribute the magnitude of disturbance for five different distribution, which are following the threshold frequency value for each steps. This approach however need extra adjustment of shedding steps for frequency control in order to minimize the disconnection of loads. This procedure actually can cause the large frequency decay in the system, hence delay the load shedding action during disturbance.

During system disturbance, the active power deficit is always accompanied with reactive power deficit. It may be noted that the value of active and reactive power loads can change during system disturbances. This can lead to changes in active and reactive power values of loads in the system. In order to highlight this issue, the author in (Prasetijo et al., 1994) used the voltage decay to determine the location of disturbances in the system. Furthermore, authors have considered voltage dependencies instead of frequency decline to estimate power imbalance by using equation (2.4) - (2.6) as reported in (Rudez et al., 2011a, 2011b). However, the author claimed that it's difficult to get the relation of voltage dependence coefficient with the power imbalance estimation.

$$P_{def} = g_1 \times \left(\frac{df_{COI}}{dt} \right) + g_2 \tag{2.4}$$

Where the function of g_1 and g_2 are defined as:

$$g_1 = \left(\frac{2 \times H_{COI}}{f_n} \right) \times 100 \tag{2.5}$$

$$g_2 = \sum_{i=1}^{m} P_{LO,i} \times \left[\left(\frac{U_i}{U_{O,i}} \right)^{\alpha i} - 1 \right] \times \frac{100}{P_{LO}} \tag{2.6}$$

Another issue associated with system disturbances is the occurrence of severe fault that could lead to various forms of instabilities conditions either frequency instabilities, voltage instabilities or both. Adaptive load shedding scheme has another limitation that commonly, frequency and voltage analysis are design independently to react following system disturbances. Due to this, some report highlights to take consideration of frequency and voltage simultaneously for adaptive UFLS scheme. In (Prasetijo et al., 1994; Saffarian et al., 2011), the loads which are suffer with higher voltage decay is shed sooner. Indirectly, the location of load shedding becomes dependent to the location of disturbances and voltage profile. Another approach proposed in (Tang et al., 2013a), has considered the reactive power together with active power in the load shedding strategy. The author claimed that the proposed approach has consequently addressed the frequency and voltage stability issues together.

This adaptive technique enhances the reliability of traditional load shedding, but the frequency changes upon system disturbance makes this approach suffer from un-optimum load shedding. As reported in (Zin, Hafiz, & Wong, 2004), the overshoot in frequency response shows that some extra load have been shed. In (J. Laghari et al., 2015), the flexibility of loads in random priority provide the optimal load shedding by selecting the least error between total load shed and total load amount. The author used 2 different type of DG (mini hydro and biomass) in order to test the effectiveness of proposed scheme. The frequency responses without overshoot proven that the proposed scheme has an ability to achieve the optimum load shedding.

In the islanded distribution system, special attention of load shedding scheme have been proposed in (Gu et al., 2013; M. Karimi et al., 2012; Ketabi et al., 2014; Mahat et al., 2010a; Mokari-Bolhasan et al., 2014). In islanded distribution system, the system frequency drop could be more severe due to limitation of the system inertia. The load shedding scheme should be fast and efficient to recover the system frequency. The effectiveness of the proposed scheme was validated through the frequency performance after load shedding process in (M. Karimi et al., 2012). Although these schemes can solve the frequency deficiency in islanded area which is connected to mini hydro generation, however it still has limitations to be implemented for large scale network system and does not has the ability to cope with various form of instabilities faults in the system. In (Gu et al., 2013; Ketabi et al., 2014), the author presents the load shedding for islanded micro grid system. The author in (Ketabi et al., 2014), proposed the load shedding which is considered the variations of power generations during the process. Through this, the different type of DG (wind turbine, diesel generator and photovoltaic) is adopted to test the proposed algorithms. Due to several type of DG (wind turbine, micro turbine and photovoltaic) as presented in (Gu et al., 2013), the author proposed the equivalent inertia constant to restore the frequency stability. In (Mahat et al., 2010a), the author proposed the load shedding based on the ROCOF, customer's willingness to pay and load histories in order to stabilize the system frequency. From this, the wind turbine and gas turbine is used in the test system. Another optimal load shedding technique is proposed in (Mahat et al., 2010b), where the load is shed according to the load ranking developed from the most of load that willing to pay for electricity. This technique has been improved by (Mokari-Bolhasan et al., 2014), where the new centralized load shedding has been proposed. The author proposed new objective function to minimize the load shedding penalty that is paid by the distribution network operator.

2.10.3 Intelligent UFLS technique

Intelligent UFLS scheme is a technique that use the computational intelligence techniques in the load shedding process (J. Laghari et al., 2013). This scheme offers extra advantages over conventional technique in problem solving involving the nonlinear problems. The implementation of intelligent techniques in power systems has increased since the late of 1980s (J. Laghari et al., 2013). The intelligent techniques also has been applied for load shedding scheme (Shokooh et al., 2005). The author in (Shokooh et al., 2005) highlight the needs of system capabilities and dynamic knowledge base following system disturbances for intelligent load shedding scheme.

Figure 2.8 shows several techniques that have been proposed for computational intelligent load shedding as discussed in (J. Laghari et al., 2013).

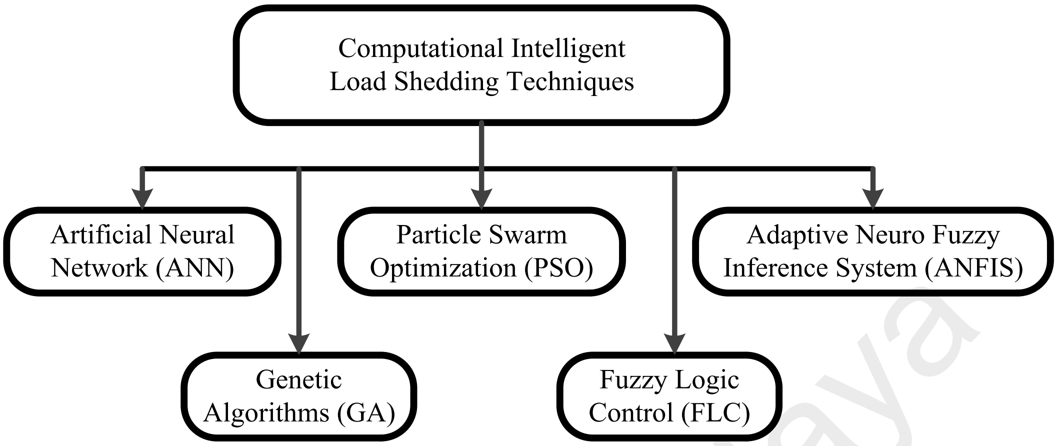


Figure 2.8: Intelligent load shedding techniques

As reported in (Hooshmand et al., 2012; Moazzami, 2010), the author proposed the optimal load shedding scheme based on Artificial Neural Network (ANN) for isolated power system. The load shedding scheme based on ANN has performed the transient stability analysis of an actual power system, in order to solve the minimum load shedding as reported in (Cheng-Ting Hsu et al., 2011; C-T Hsu et al., 2005). However, there are some limitations of ANN, where the satisfactory result can achieve for known cases. Thus, the ANN fails to predict the accurate analysis for unknown or varying cases (J. Laghari et al., 2013).

Apart from ANN, some authors have proposed the intelligent UFLS scheme based on Genetic Algorithms (GA) in order to solve the optimal load shedding problem as reported in (Chen et al., 2011; Sanaye-Pasand et al., 2005). In (Chen et al., 2011), the single machine infinite bus system has been tested for considering the load demand for 12 months for the proposed GA technique. The analysis result is compared with conventional 8 stages of UFLS. Although both methods can return the system into the equilibrium condition after disturbances, GA based method offer extra advantages, where the load shedding technique shed the minimum loads in the system.

In the islanded distribution system, the intelligent load shedding scheme based on Fuzzy Logic Control (FLC) and Comprehensive Learning Particle Swarm Optimizer (CLPSO) have been proposed in (El-Zonkoly et al., 2013; J. A. Laghari et al., 2014). In (J. A. Laghari et al., 2014), the FLC is proposed to estimate the amount of load shed. The input of fuzzy controller is system frequency and ROCOF for islanded distribution system. Another intelligent load shedding scheme based on CLPSO is proposed in (El-Zonkoly et al., 2013) to get the optimum amount of load shedding.

All of the UFLS techniques discussed above have advantages and also limitations. Choosing a particular technique for load shedding execution needs a lot of consideration in aspect of operating conditions, level of severe disturbance, value of frequency decline and other parameters. Table 2.4 shows the summary of comparison between traditional, semi-adaptive and adaptive scheme of load shedding.

Table 2.4: Comparison between load shedding techniques

Technique	Reference	Advantages	Disadvantages
Conventional	(Junjie et al., 2013), (J. Laghari et al., 2013)	• Simple • Easy to implement	• Lack of information on magnitude of disturbances. • Shedding the fixed percentage of loads during disturbances.
Adaptive		• Accurate to determine the amount of load shedding • Reliable and Robust	• Optimum load shedding issues must be considered for the proposed adaptive load shedding. • Not guarantee to adapt with a combination of frequency and voltage instabilities in the system.
Intelligent	(J. Laghari et al., 2013)	• Has an ability to provide the optimum of the load shedding scheme • Efficiently applied in modern and complex power system	• Not guarantee to adapt with a combination of frequency and voltage instabilities in the system. • Involved with time consuming in its implementation.

2.11 Load Shedding Technique based on Voltage Stability (VS) Index

In the present scenario of increasing load demand and exploitation of the existing power system structure, the occurrence of system collapse is widely extended rather than before. The fluctuation of voltage magnitude will initiate instable point not only in transmission system as well as in distribution. In order to address this issue, many researches have been paid more attention to address the issues of VS by introducing several stability index formulations to identify the nodes or lines that are nearly to collapse. The VS is known as the indicator to determine the status condition either for bus or line system according its particular assumption formulated. In the present work, the

VS can be classified either in bus or line of the system. From the VS analysis, the critical buses in the system can be identified and certain measures have to be taken in order to avoid any incidence of voltage collapse. The abnormal voltage condition mainly associated with voltage failures and could lead to partial and final collapse. Basically, the abnormal voltage condition problem happens due to several reasons as follows (El-Amary et al., 2010):

- Increased loading on power system.
- High transmission impedance
- Insufficient reactive power to supply

In the presence of abnormal voltage condition, the system is approach stability limit condition and closer to the maximum power transfer limits. This contributed the uneconomical losses and the voltage magnitude is progressively decline. The unstable voltage condition not only in interconnected power system, also in islanded power system (El-Amary et al., 2010). In this regard, this research presents the contribution of online VS analysis as main priority in load to be shed. The voltage stability is analysed for each bus in the test system.

2.12 Load Shedding Schemes based on Voltage Stability (VS) Index: A Review

Currently, some research highlights the importance of VS index as an indicator to identify the stability for the whole system during dynamic conditions. The VS index is widely used in power system problems. In (Mahmoud Moghavvemi et al., 1999), the VS index is used for predicting contingencies outage of the lines, optimal location for DG allocation (Abdel-Akher et al., 2011), improve the line performance and VS margin (Valujerdi et al., 2012) and detection of voltage instabilities (Kessel et al., 1986).

The application of VS index has also been applied for the load shedding in a power system. In (El-Sadek et al., 1999), the authors proposed the optimum load shedding to avoid voltage instabilities during emergency conditions. In this scheme, the modification of L-indicator index is used to obtain the optimum load shedding. Despite this scheme achieved the optimum load shedding, the computational time of control strategy is not considered in the proposed scheme. The proposed scheme should be fast enough to respond and bring the system back to the normal permissible limit.

In order to fill this gap, the author in (Nizam et al., 2007) proposed the Power Transfer Stability Index (PTSI) to shed the load with the minimum allowable time. From this, the PTSI index is used as indicator to determine the weakest bus in the system to shed. The highest value of Fast Voltage Stability Index (FVSI) proposed in (Musirin et al., 2002a) indicated the weakest bus and given priority to be shed. The proposed FLC based on VS indicator offer lower execution time as presented in (Sasikala et al., 2011). The optimization algorithms can offer advantages that can improve the load margin (Echavarren et al., 2006) and can maintain the threshold value for all load bus voltage within limits (Arya et al., 2005).

In (El-Sadek et al., 1999; Nizam et al., 2007), a simple load flow analysis is used to analyse the VS index for all buses. However, in the modern power system network, it needs the Optimal Power Flow (OPF) solution. The OPF is the optimization constraint that can minimize the generation cost and satisfy the equality and inequality constraints. Due to this reason, research in (Kanimozhi et al., 2014) proposed the computational VS index using weighted sum GA to restore the power flow solvability. From this approach, the New Voltage Stability Index (NVSI) is adopted to determine the weakest bus in the system.

Though extensive research for load shedding based on VS index has been proposed in references (Arya et al., 2005; Echavarren et al., 2006; El-Sadek et al., 1999; Kanimozhi et al., 2014; Nizam et al., 2007; Sadati et al., 2009; Sasikala et al., 2011), these proposed schemes are mainly implemented for transmission system. However, relatively little contribution is reported on the application of load shedding in distribution system. This is due to fact that compared to the transmission system; distribution networks have different characteristics, such as radial structure and high *R/X* ratio, which makes the analysis more difficult.

Hence, to improve this barrier, some works reported in (Eminoglu et al., 2007; N. Yusof et al., 2014) have been done to propose the load shedding based on VS index for distribution system. In (Eminoglu et al., 2007), the author proposed the Stability Index (SI) based on transferred active and reactive power for the radial distribution line. The author claimed that the proposed index is robust and can be utilized the weakest bus in any operating point in the linear distribution system. The author presented the Fast Voltage Stability Index (FVSI) in (N. Yusof et al., 2014) which gives the priority of weakest bus to non-vital load during load shedding following instability conditions. FLC based UVLS scheme using Risk of Voltage Instability (Balaguer et al.) indicator for averting the voltage collapse is proposed in (Sasikala et al., 2011).

Table 2.5 summarizes the VS index applied for load shedding in transmission and distribution system. From this table, this research proposes the FVSI index for load shedding in transmission and distribution system. Although some research has been carried out for VS in load shedding, however this research has not explored yet.

Table 2.5: Voltage stability index proposed for load shedding

Research Paper	VS index	Equations	Critical Value	Assumption for VS index	Applied in distribution	Applied in transmission
(El-Sadek et al., 1999)	L indicator index	$L_j = \left\| 1 - \frac{\sum_{i \in \alpha G} F_{ij} V_i}{V_j} \right\|$	1	The index is derived by taking assumption that all generator voltage remain unchanged (Kessel et al., 1986). However, the voltage magnitude might be change due to sudden disturbances in the system.	-	√
(Nizam et al., 2007)	PTSI	$PTSI = \frac{2 S_L Z_{Thev} (1 + \cos(\beta - \alpha))}{E^2_{Thev}}$	1	From this index, the Y ≈ 0 (Modarresi et al., 2016)	-	√
(Musirin et al., 2002a)	FVSI	$FVSI = \frac{4 Z_{ij}^2 Q_r}{V_s^2 x_{ij}}$	1	This index is formulated by taking assumption that δ is normally small, then Rsin δ ≈ 0 and Xcos δ ≈ X (Musirin et al., 2002a).	-	√
(Sasikala et al., 2011)	L indicator index	$L_j = \left\| 1 - \frac{\sum_{i \in \alpha G} F_{ij} V_i}{V_j} \right\|$	1	The index is derived by taking assumption that all generator voltage remain unchanged (Kessel et al., 1986). However, the voltage magnitude might be change due to sudden disturbances in the system.	-	√
(Eminoglu et al., 2007)	SI	$SI = 2V_s^2 V_r^2 - V_r^4 - 2V_r^2 (PR + QX) - \|Z\|^2 (P^2 + Q^2)$	0	From this index, the Y ≈ 0 (Modarresi et al., 2016)	√	-
(N. Yusof et al., 2014)	FVSI	$FVSI = \frac{4 Z_{ij}^2 Q_r}{V_s^2 x_{ij}}$	1	This index is formulated by taking assumption that δ is normally small, then Rsin δ ≈ 0 and Xcos δ ≈ X (Musirin et al., 2002a).	√	-

2.13 Chapter Summary

This chapter has presented overview on the distributed generation, their benefits, and its impact to power system network. It also discussed operation modes of DG. The major issue that has been elaborated throughout the chapter is islanding. Islanding is not permitted due to various technical challenges that have been discussed in this chapter. However, due to the benefits it can bring, some utilities have initiated islanding and various standards have also been developed for successful intentional islanding operation.

Apart from that, this chapter has discussed on various load shedding techniques for islanded distribution system. From this, the load shedding based on VS index is presented. Based upon the literature review of load shedding techniques based on VS index, it has been observed that not much work focusing on load shedding based on VS index implemented in distribution system. Most of previous works have used the VS index for load shedding in transmission line only. Hence, this research proposes a new load shedding technique based on combination of VS and frequency for islanded distribution network connected with rotating type distributed generation.

CHAPTER 3: PROPOSED UNDER FREQUENCY LOAD SHEDDING SCHEME

3.1 Introduction

In previous chapter, the literature review regarding the application of load shedding scheme for islanded distribution system has presented. When islanding occurs in the distribution system, the system frequency and voltage might be severe with further decline due to mismatch between generation and load generation. However, improper load shedding would lead to high number of power blackouts due to insufficient load shed. This situation raised the issues about the ability and reliability of existing adaptive Under Frequency Load Shedding Scheme (UFLS) and conventional load shedding. To address this issue, this chapter presents the new load shedding scheme for islanded distribution system.

3.2 Concept of Proposed UFLS Scheme I

In this research, the system frequency and Voltage Stability (VS) are considered simultaneously in the control strategy. The system frequency is monitored in the event of disturbances. The power imbalance is determined based on system frequency deviation based on Rate of Change of Frequency (ROCOF) calculation. In terms of VS, the VS index is calculated and analyzed for each bus in the system. According to the VS value, the critical buses in the system can be recognized. In this research, the proposed algorithms are designed to keep updating VS index. In other words, the VS value is monitored based on online system controller throughout the simulation process. This process can ensure the ranked of VS index is developed based on the updated of stability condition of the buses. In this research, the proposed UFLS scheme I is referred as $UFLS_{VS}$.

3.3 Methodology of Proposed UFLS Scheme I

The aim of the proposed of UFLS Scheme I is to shed the critical buses during system disturbances in the system. Figure 3.1 shows the overall concept for proposed $UFLS_{VS}$.

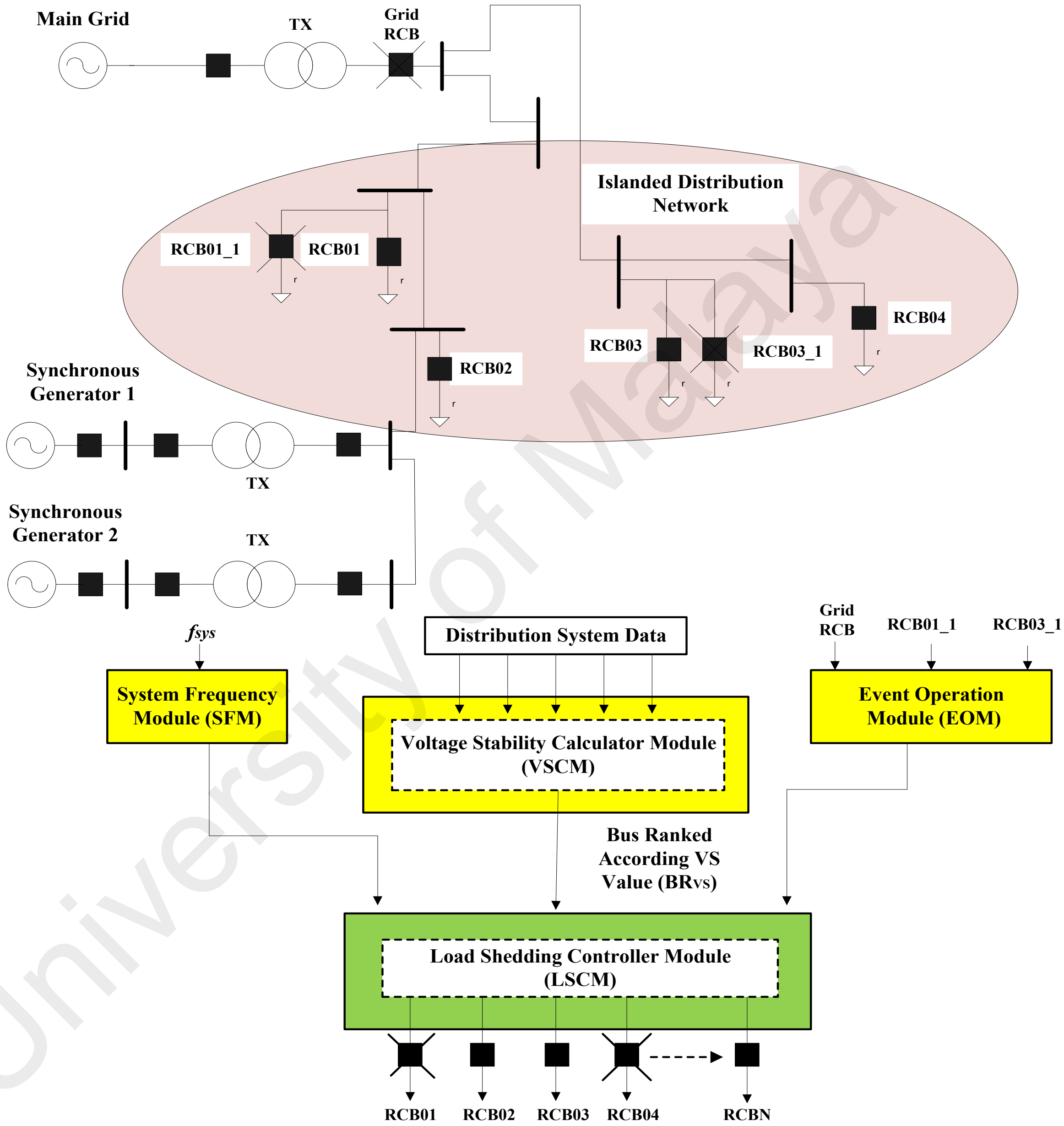


Figure 3.1: Overall concept of the proposed $UFLS_{VS}$

In general,the proposed scheme consists of four main modules and explained in the following sections.

1) Event Operation Module (EOM)
2) System Frequency Module (SFM)
3) Voltage Stability Calculator Module (VSCM)
4) Load Shedding Controller Module (LSCM)

3.3.1 Event Operation Module

In the proposed scheme, the Event Operation Module (EOM) is designed to monitor the real-time measurements of the distribution network. The main operation of EOM is in the detection of islanding events in the distribution system. The EOM is designed to simultaneously monitor the Remote Circuit Breaker (RCB) status in the main substations. The EOM recognizes the islanding operation by monitoring the grid RCB in the system. Once the EOM detects the grid RCB open, the network is islanded. Hence, the power imbalance value is then calculated by related measurement units' due to mismatch between generation and load demand. The corresponding power imbalance value is then transmitted to the Load Shedding Controller Module (LSCM).

Figure 3.2 shows the EOM flow chart operation. The EOM continuously monitor not only the grid breaker (Grid RCB) as well as the breaker in all buses in the system. The islanding event is detected when the EOM received the open signal of grid RCB. Then, due to consequence from islanding, the power imbalance is calculated and send to the LSCM for the load shedding purposes.

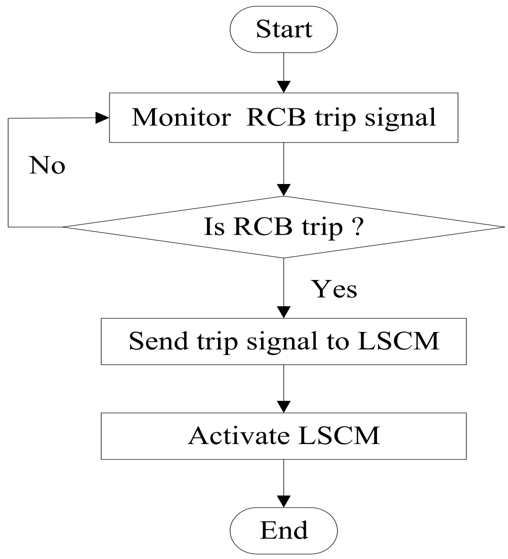


Figure 3.2: Flow chart of event operation module

By implementing the EOM, it is possible to report all the events occur in the system either islanding or sudden load increment in the system. In case where the sudden load increment in the network, the EOM will detect the trip signal from RCB01_1 and RCB03_1 breaker due to the sudden increment of active power at buses. The load increment event is detected, when the total active power load is more than the total generation. In this case, the total of 0.5MW of active power load is injected to the system. Hence, the EOM will send the signal to the LSCM for load shedding purposes. The LSCM will decide an appropriate control action to determine the power imbalance based on the event-based strategy. Subsequently, by implementing the EOM, all events resulting from the trip signal for Grid RCB, RCB01_1 and RCB03_1 will be recorded and monitored in order to provide a load shedding action which is implemented through LSCM.

3.3.2 System Frequency Module

Figure 3.3 represents the flowchart of overall performance of the System Frequency Module (SFM) operation. The SFM continuously monitors the status of system frequency (f_{sys}) either during grid connected or islanding operation. In Addition, the SFM always monitor and update the information of f_{sys} during system steady state and disturbances.

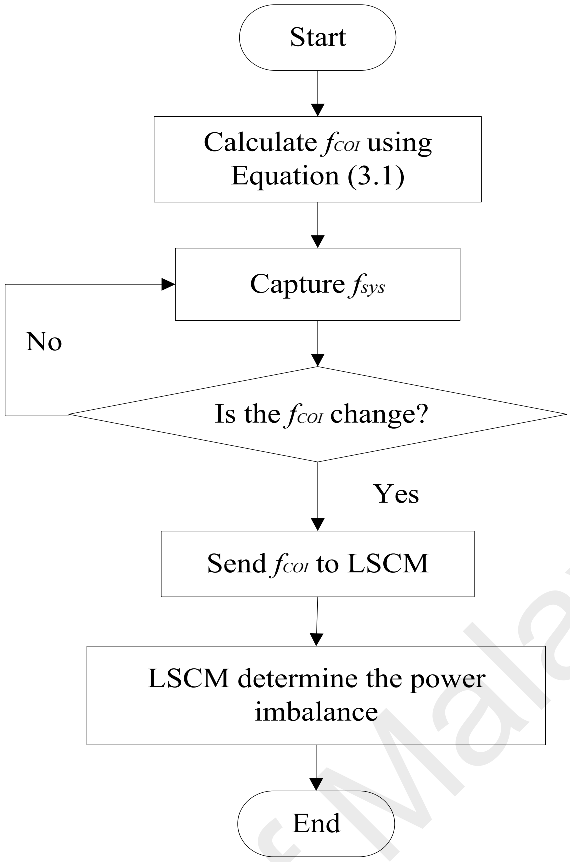


Figure 3.3: Flowchart of system frequency module

In this research, the test system has many interconnected equipments, each equipped with several generators and loads. In this connection, it might be difficult to maintain the synchronism between various part of a power system. This happens due to several reasons such the increasing size of the system network. Hence, it is required to consider all machines located at any point in the system. To implement this, all the machines will be considered at every location in the test system. Also the machines which are not separated by lines are lumped together and considered as one equivalent machine. Due to this, this research considered the equivalent Centre of Inertia Frequency (COIF) as given in equation (3.1) to estimate the equivalent COIF for different rating of generators.

$$f_{COI} = \frac{\sum_{i=1}^{N} H_i \times f_i}{\sum_{i=1}^{N} H_i} \tag{3.1}$$

Where ΔP is power imbalance, H_i is the inertia constant of i^{th} generators (s), f_n is the rated frequency (Hz), df_{COI}/dt is the rate of change of inertia frequency (Hz/s), f_{COI} is the frequency of centre of inertia (Hz) and f_i is frequency of i^{th} generator (Hz).

3.3.3 Voltage Stability Calculator Module

The VS value of each bus in the network is calculated and monitored through Voltage Stability Calculator Module (VSCM). The proposed VSCM algorithm considers the real data measurements from the distribution network as shown in Figure 3.4. From the value of VS index for all buses in the network, these values are sorted from critical value to stable value. The critical VS value indicates the weakest bus in the system. Meanwhile, the stable VS value indicates the stable bus in the system. Table 3.1 lists the summarizes critical and stable value for all VS index implemented in this research. It may be noted that in the proposed VSCM, the Bus Ranked is done according to VS Value, referred as BR_{VS} throughout this research. The BR_{VS} is transmitted to the LSCM to perform the load shedding process.

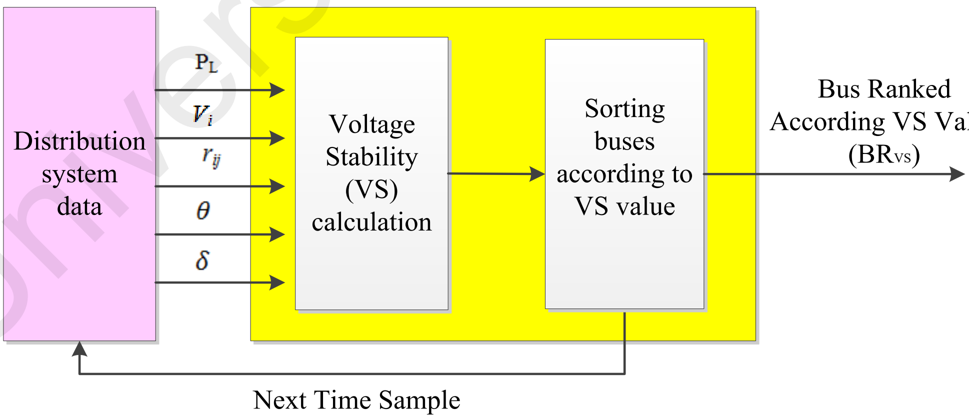


Figure 3.4: Overall concept for voltage stability calculator module

Table 3.1: Voltage stability index

Proposed Index	VS index	Equations	Critical Value	Stable Value	Description
(Eminoglu et al., 2007)	SI	$SI = 2V_s^2 V_r^2 - V_r^4 - 2V_r^2 (PR + QX) - \lvert Z \rvert^2 (P^2 + Q^2)$	0	1	- This index considers transferred active and reactive power of the distribution line.
(Chattopadhyay et al., 2014)	VSI	$VSI = \frac{4Q_r (R + X)^2}{X(V_s^2 + 8RQ_r)}$	1	0	- This index assume that the voltage angle is very small and the line shunt admittance is neglected
(Aman et al., 2012)	PSI	$PSI_j = \frac{4r_{ij}(P_{Lj} - P_{DG})}{[\lvert V_i \rvert \times \cos(\theta - \delta)]^2}$	1	0	- The "*j*" referring the receiving end of two buses. The value of P_{DG} is only available a DG generator is connected. Otherwise, the P_{DG} value will be "0". For situation where P_{DG} is larger than P_{Lj}, a negative value of PSI will be obtained.
(Musirin et al., 2002b)	FVSI	$FVSI = \frac{4Z_{ij}^2 Q_r}{V_s^2 x_{ij}}$	1	0	- The FVSI referred as the mathematical model of line stability index. This technique proposed the FVSI as indicator to determine the point of voltage collapse, maximum permissible load and the most critical line in the system.
(Yazdanpanah -Goharrizi & Asghari, 2007	NLSI	$NLSI = \frac{P_r R + Q_r X}{0.25V_s^2}$	1	0	- The angular difference between the sending and receiving voltage is assumed to be very small ($\delta \approx 0$). Also, the line shunt admittance is neglected in this index.
(M Moghavvemi et al., 2001)	Lp	$L_p = \frac{4RP_r}{(V_S \cos(\theta - \delta))^2}$	More than 1	0	- In this index, effect of reactive power and line shunt admittance is neglected for this index. Hence, it is assumed that only active power affects the line Vv.
(M Moghavvemi et al., 1998)	Lmn	$L_{mn} = \frac{4x_{ij} Q_r}{[V_s \sin(\theta - \delta)]^2}$	More than 1	0	- This index represented the stability value for each line connected between two busbars in the system and can be accurately predicted the voltage collapse.

Figure 3.5 illustrates the flowchart of VSCM operation. In this proposed scheme, the VSCM is designed to keep updating the real data parameters from the distribution system during system steady state as well as in dynamic condition. During system islanding, the voltage level of buses in the network could be decreased and approach its stability limit. This situation would alter the BR_{VS} and this change would also take place during the process of load shedding. To address this issue, the VSCM will recalculate the VS value then send to the LSCM. Hence, the implementation of the VSCM may provide an appropriate load shedding through the LSCM.

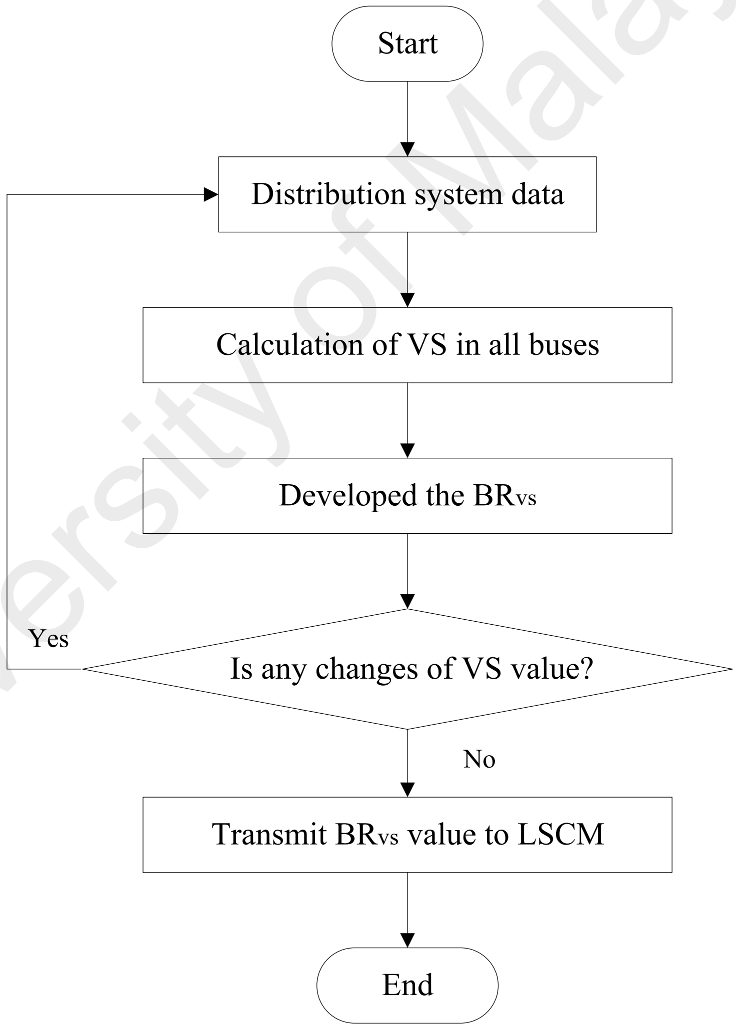


Figure 3.5: Flowchart of voltage stability calculator module

3.3.4 Load Shedding Controller Module

The Load Shedding Controller Module (LSCM) will only activate its algorithm when it receives a signal from EOM, indicating the formation of islanding or load increment in the system. Also, the system frequency performance is monitored through the information received from the SFM. The LSCM will initiate the corresponding load feeder to be removed in the distribution system according to the power imbalance estimation. The amount of power imbalance is calculated either based on a power imbalance calculation (event-based strategy) or ROCOF (response-based strategy). The LSCM will shed the load based on the BR_{VS} received from VSCM, where the highest BR_{VS} is prioritized for load shedding.

The overall algorithm of the proposed scheme is shown in Figure 3.6. In this proposed scheme, the LSCM continuously checks the received signal and information from the EOM and SFM to define an appropriate UFLS strategy. In this research, the proposed LSCM consists two different strategies for determining the power imbalance as explained in the following sections.

1) Event based strategy – when the grid is disconnected from the distribution network.
2) Response based strategy – when sudden load increment in the islanded distribution network.

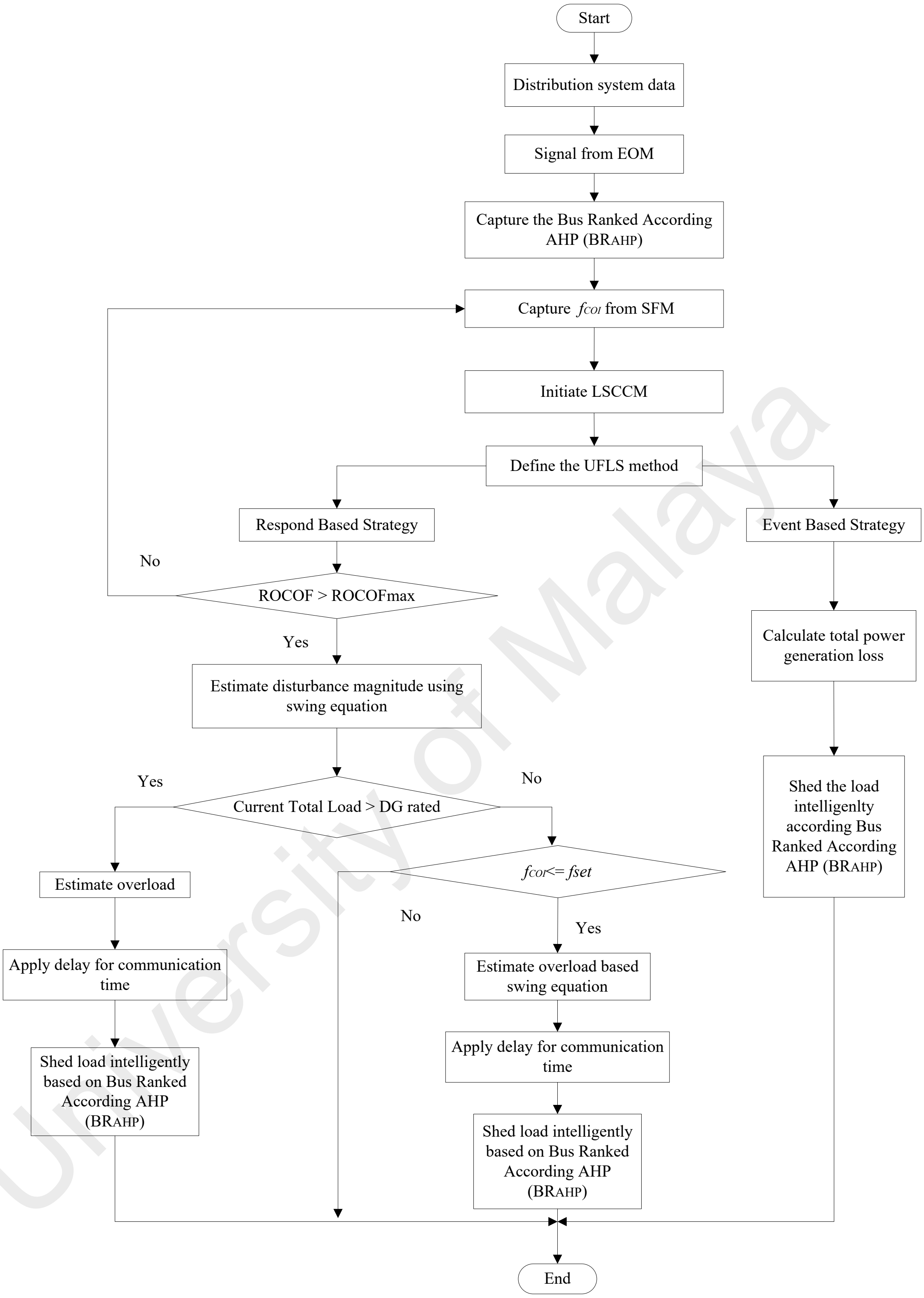


Figure 3.6: Flowchart of the proposed load shedding controller module

3.3.4.1 Event Based Strategy

Event based strategy is applied when the system experiences insufficient power supply for the load demand resulting from islanding. During system islanding, the power generation could be unable to supply the load demand in the islanded network. This situation caused the voltage magnitude decrement and further declining of system frequency. Hence, the proposed strategy initiated the event-based strategy to recover the system frequency and the most critical bus to collapse is given priority to be shed. The event-based strategy is initiated when the LSCM received the tripping signal of the grid breaker through EOM. Then, the mismatch of active power between generation and total load demand is calculated using the formula in equation (3.2):

$$\Delta P = [(P_{grid} + P_{DG}) - (P_{load})] \tag{3.2}$$

Where:

ΔP	=	imbalance power between generation and load consumption
P_{grid}	=	grid generation
P_{DG}	=	mini hydro generation
P_{load}	=	total active power injected to each load in the system

According to the estimated power imbalance value, the load is shed based on the BR_{VS} signal received from the VSCM.

3.3.4.2 Response Based Strategy

In the proposed scheme, the LSCM is activated during sudden disturbances occurs in the islanded system. In case where the sudden load increment in the system, the response-based strategy is employed to solve the issues of imbalance power between generation and load demand. In this case, the magnitude of ROCOF from the swing equation is used to estimate the power disturbance.Mathematically, the total power imbalance due to load variation for *N* generators can be computed by using equation (3.3).

$$\Delta P = ((2 \times \sum_{i=1}^{N} H_i / f_{COI}) \times (df_{COI} / dt)) \tag{3.3}$$

Where:

H_i	=	inertia constant of i^{th} generator (seconds)
df_{COI} / dt	=	rate of change of COIF (H/s)
f_{COI}	=	rated frequency (Hertz)
N	=	number of DGs
ΔP	=	power imbalance

Based on equation (3.3), the ROCOF will take into account the rate of change of COIF in the distribution system to determine the exact amount of the power imbalance. In order to avoid the unnecessary activation of the load shedding for very small disturbances, a threshold called $ROCOF_{max}$ is introduced. The threshold value is set according to the smallest value of active power load of the distribution system. The value set for this threshold is 50 kW, which is system specific, and can be adjusted accordingly. If the estimated amount exceeds this threshold, the proposed technique begins its next step; otherwise, the Distributed Generations (DGs) unit remain operating without any load shedding. The load is shed according to the BR_{VS} from VSCM. It should be noted that the magnitude of the disturbance is closely related to the frequency response of the system. Thus, the large occurrence of disturbance might cause the frequency to exceed the allowable f_{set} (48 Hz).

3.4 Concept of Proposed UFLS Scheme II

The proposed UFLS Scheme II is slightly different from the proposed UFLS Scheme I in determining the BR_{VS} for load shedding. The UFLS Scheme I uses the VS value to determine the BR_{VS} for load shed. This makes the UFLS Scheme I to solely depend upon VS of buses without considering the Load Category (LC) as another factor in BR_{VS}. In practice, the LC can be categorized as vital, semi-vital and non-vital load. This LC is an important factor to be considered for load shed. In a real situation, the vital load (eg : hospital, factory) should be avoided from the load shedding process since these vital loads are crucially required.

From the UFLS Scheme I, it might happen that the critical bus in BR_{VS} is the vital load or the next stage in BR_{VS} is the vital bus. From this, the load shedding action can create the problems where vital load such as a hospital will shed. To overcome this limitation, the UFLS Scheme II employs both factors, VS and LC to develope the Bus Ranked according to Voltage Stability and Load Category, referred as BR_{VS_LC} for load shed. This approach is able to recover the system frequency and enhance the performance of voltage magnitude in the system. The methodology of the proposed UFLS Scheme II is presented in the following section. In this research, the proposed UFLS scheme II is referred as $UFLS_{VS\_LC}$.

3.5 Methodology of Proposed UFLS Scheme II

Figure 3.7 shows the overall concept of proposed of $UFLS_{VS\_LC}$. The proposed scheme is based on 2 main factors, VS and LC to determine the BR_{VS_LC}. The idea is to secure the vital load operation and then select the critical load to be shed. In general, the proposed $UFLS_{VS\_LC}$ introduce four main modules as presented in Section 3.3. However, for VSCM, the proposed $UFLS_{VS\_LC}$ employs VS and LC to determine the BR_{VS_LC}. Hence, the Stability and Load Category Module (SLCM) is introduced in UFLS $_{VS\_LC}$, to enhance the VSCM as proposed in UFLS$_{VS}$. The description of this module is explained in the following sections.

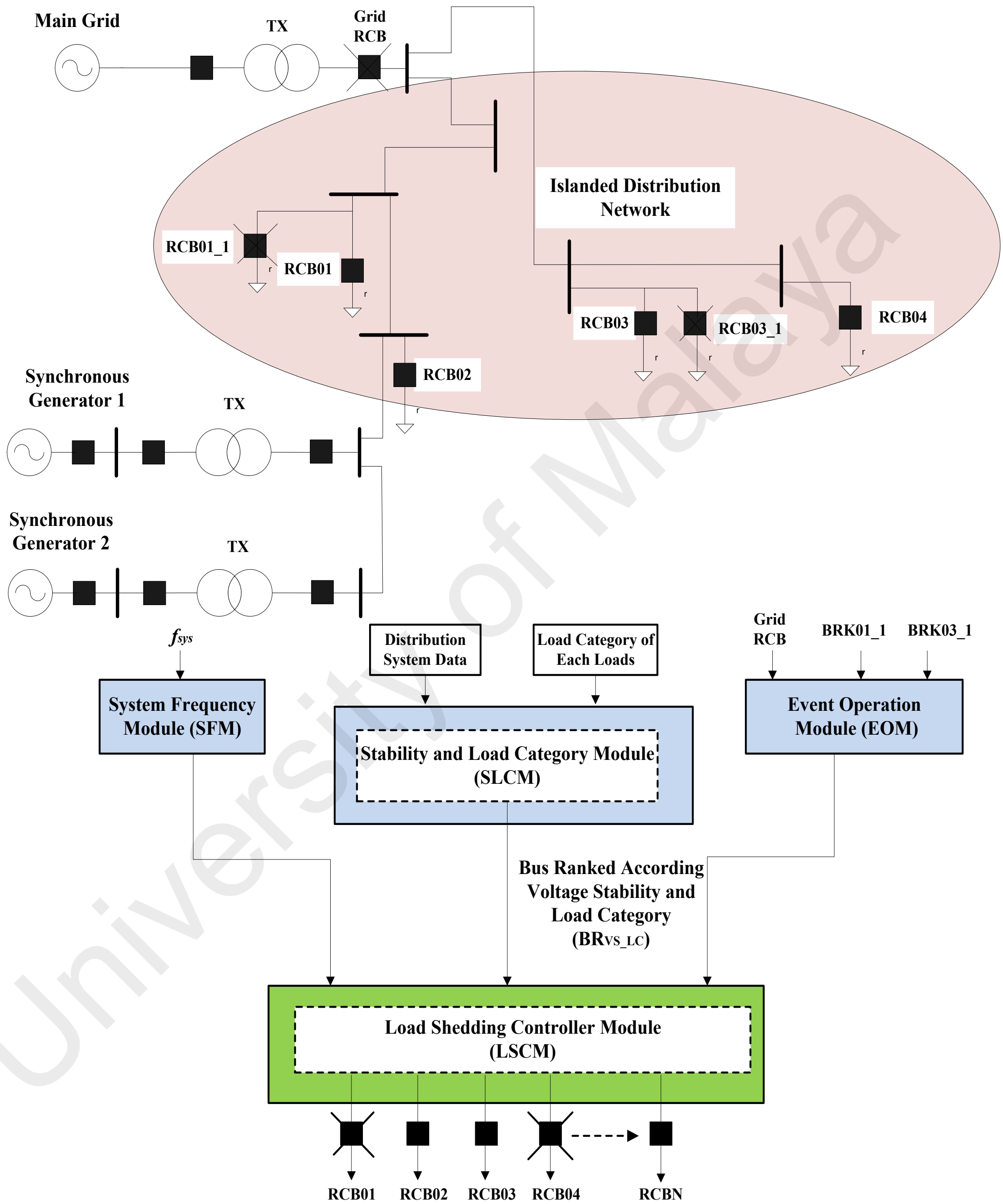


Figure 3.7: Overall concept of UFLS$_{VS_LC}$

3.5.1 Stability and Load Category Module

Figure 3.8 shows the overall concept of the proposed Stability and Load Category Module (SLCM). The SLCM module will monitor the VS and check the LC in all buses in the network. Initially, the SLCM will calculate the VS for all buses. After that, $UFLS_{VS\_LC}$ will search the vital and semi-vital load in the system. These load categories will be avoided to shed during system disturbances.

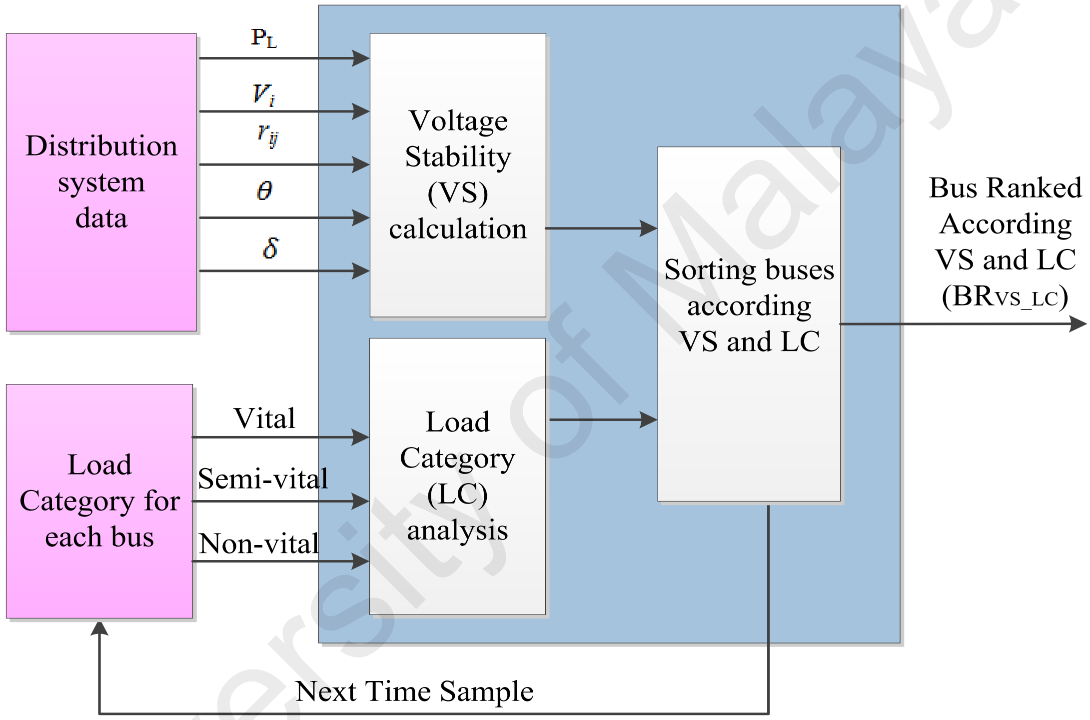


Figure 3.8: Overall concept for stability and load category module

For proposed $UFLS_{VS\_LC}$, the non-vital load will be given priority to be shed. The SLCM will record the non-vital load and ranked all the group of non-vital loads in BR_{VS_LC}. In the BR_{VS_LC}, the highest ranked is indicated as the critical bus and given priority to shed. Then, the BR_{VS_LC} is transmitted to the LSCM for load shedding as shown in Figure 3.9.

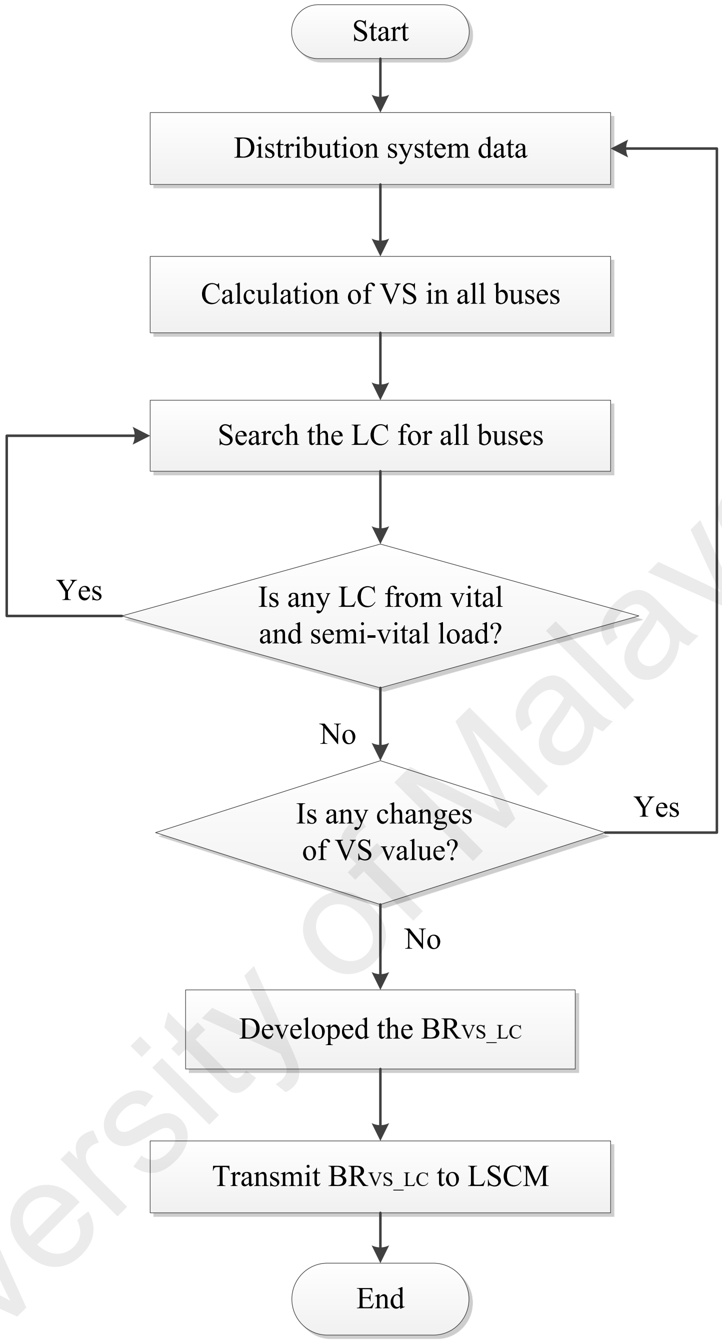


Figure 3.9: Flowchart of stability and load category module

3.6 Chapter Summary

This chapter has presented the background, concept and methodologies of two proposed load shedding scheme, $UFLS_{VS}$ and $UFLS_{VS\_LC}$ for successful islanding operation. This proposed scheme highlights extra advantages, where the VS are considered in the proposed module. In the proposed schemes, there are four main modules introduced for both scheme ($UFLS_{VS}$ and $UFLS_{VS\_LC}$). The description for each module is presented in this chapter. The proposed schemes are based on the ROCOF and power swing equation to determine the power imbalance during system islanded and sudden load increment. For $UFLS_{VS}$, the proposed scheme employed the VS to determine the BR_{VS}. On the other hand, the proposed scheme II considers the combination of VS and LC to determine the BR_{VS_LC}. The LSCM is initiated to shed the load based on BR_{VS} and BR_{VS_LC} for $UFLS_{VS}$ and $UFLS_{VS\_LC}$ respectively, during system disturbances.

CHAPTER 4: PROPOSED ANALYTICAL HIERARCHY PROCESS METHOD FOR OPTIMAL LOAD SELECTIVITY

4.1 Introduction

Chapter 3 has presented the proposed Under Frequency Load Shedding (UFLS) scheme for an islanded distribution system while this chapter details the optimal selectivity of the load shedding scheme. In the proposed scheme, the least errors from the total load and power imbalance value are estimated for all possible combinations. After that, the loads to be shed is analysed by using the decision-making technique. The decision-making of Analytical Hierarchy Process (AHP) is then adopted to compare the pairwise and ensures a balanced judgment is provided in the load selectivity for load shedding scheme.

4.2 Concept of Optimal Selectivity for Load Shedding

Up till now, various UFLS has been proposed in order to realise the optimal of the load shedding scheme. However, the priority of load to be shed has not been investigated in the previous works. In this proposed algorithm, the load combination is determined according to the error value. The error is defined as the difference between the total power generation and the total load demand in the system. Based on this, two sets of load combination are selected from least error value to be implemented using the decision-making analysis for load selectivity.

The decision-making based on AHP technique is used to determine the weight value for all alternatives from the two sets of load combinations. There are two important criteria that need to be considered; stability criteria and load criteria. The best load ranked is developed from the weight value from the decision making based AHP method, referred to as the $UFLS_{AHP}$. This confirms the advantages of the proposed scheme, where the load ranked for load shed accounts for the stability and load value criteria.

4.3 Methodology of Optimal Selectivity for Load Shedding

In this section, the optimal selectivity for load shedding is proposed. Generally, there are six main modules:

1) Event Operation Module (EOM)
2) System Frequency Module (SFM)
3) Voltage Stability Calculator Module (VSCM)
4) Optimal Combination of Least Error Module (OCLEM)
5) Analytical Hierarchy Process Module (AHPM)
6) Load Shedding Controller Criteria Module (LSCCM)

It should be pointed out that the Event Operation Module (EOM), System Frequency Module (SFM), and Voltage Stability Calculator Module (VSCM) are detailed in Section 3.3. Figure 4.1 illustrates the overall concept of the proposed $UFLS_{AHP}$. It can be seen that the Bus Ranked According AHP (BR_{AHP}) is developed from the proposed AHPM. The load is shed in accordance to the BR_{AHP} during system disturbances. The description for each module is explained in the following sections:

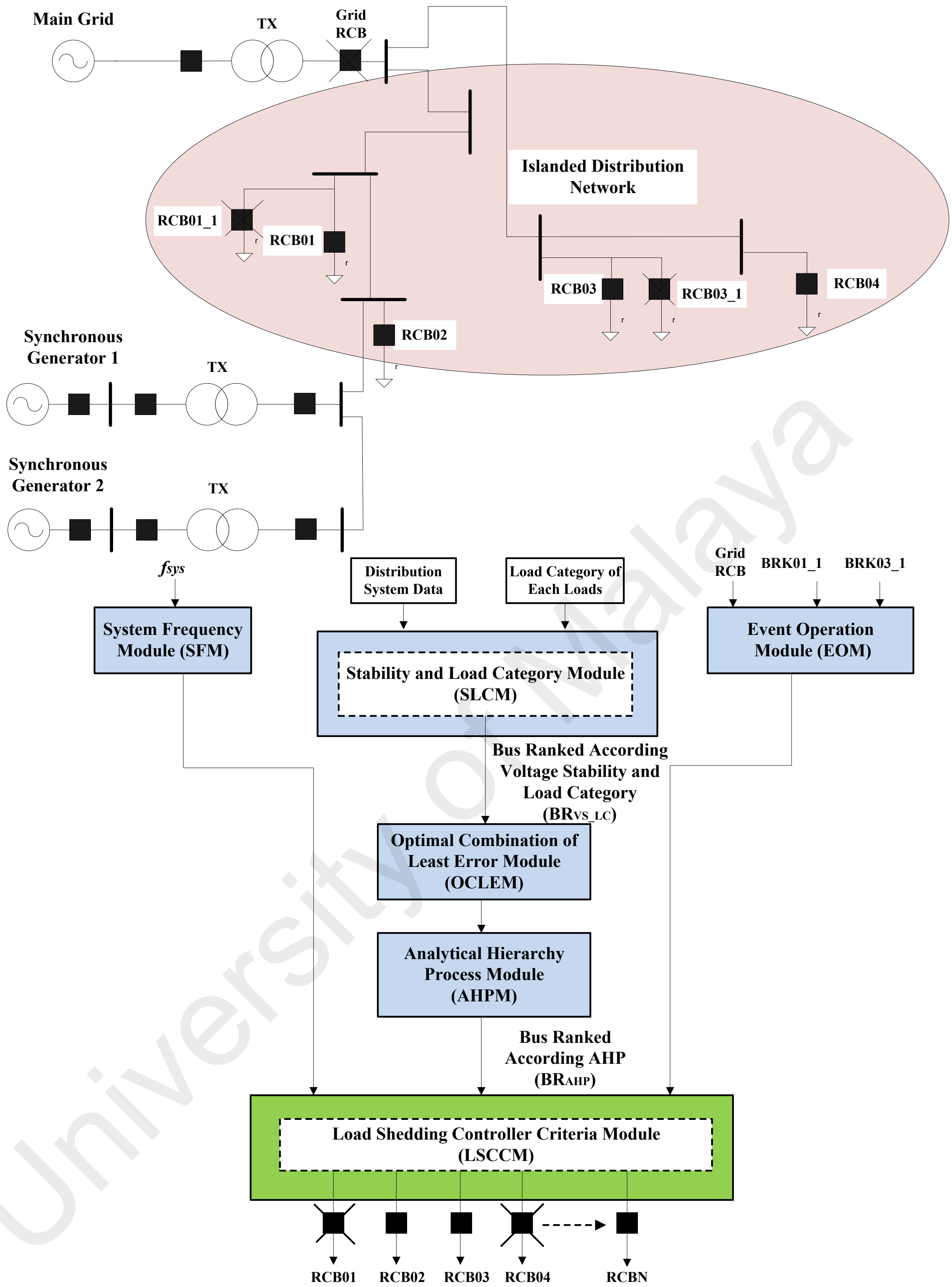


Figure 4.1: Overall concept of the proposed $UFLS_{AHP}$

4.3.1 Optimal Combination of Least Error Module

This section presents the Optimal Combination of Least Error Module (OCLEM) algorithm that is proposed in this research. It should be noticed that in this proposed algorithm, the load is selected from the proposed UFLS Scheme II, referred to as the $UVLS_{VS\_LC}$. In other words, the selection for the optimal load combination only accounted for the non-vital load on the system. Figure 4.2 shows the overall concept of the proposed OCLEM. The input for OCLEM is the bus from the proposed $UFLS_{VS\_LC}$, while the output from the OCLEM is used as the input for Analytical Hierarchy Process Module (AHPM).

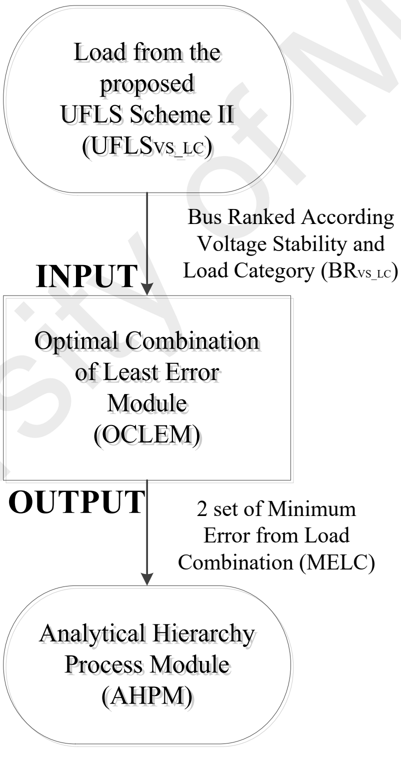


Figure 4.2: Overall concept of optimal combination of least error module

In the first step, the OCLEM is recorded the number of buses from the $UVLS_{VS\_LC}$. Then, the maximum number of possible load combinations is evaluated by using equation (4.1).

$$Maximum\ No\ of\ Combinations = 2^N - 1 \tag{4.1}$$

From equation (4.1), *N* shows the number of non-vital loads (from $UVLS_{VS\_LC}$). The next step involves calculating the absolute error for all load combinations by using equation (4.2).

$$Error_i = Imbalance\ Power - \sum P_i \tag{4.2}$$

Where:

$Error_i$	=	Absolute error for i^{th} load combinations
Imbalance Power	=	Imbalance value between total generation and total load demand during disturbances
$\sum P_i$	=	Sum of active power for i^{th} load combinations

In this research, two set combinations with Minimum Error from Load Combination (MELC) are determined. First combination and second combination of MELC are referred to as COM1 and COM2, respectively. In this case, two sets of MELC are selected to ensure that the Voltage Stability (VS) criteria are investigated in COM2 instead of COM1. This is to allow comparisons to be made between the VS criteria for all buses from these two sets of MELC. This is important, as the critical buses are not necessary located in COM1. There is a case where the highest value of VS (indicates the critical bus from VS value) is in COM2. Thus, two sets of MELC (COM1 and COM2) are selected for an accurate analysis encompassing a wide range of data analysis. Then, two sets of

MELC are transmitted to the AHPM. Figure 4.3 illustrates the proposed algorithm for OCLEM.

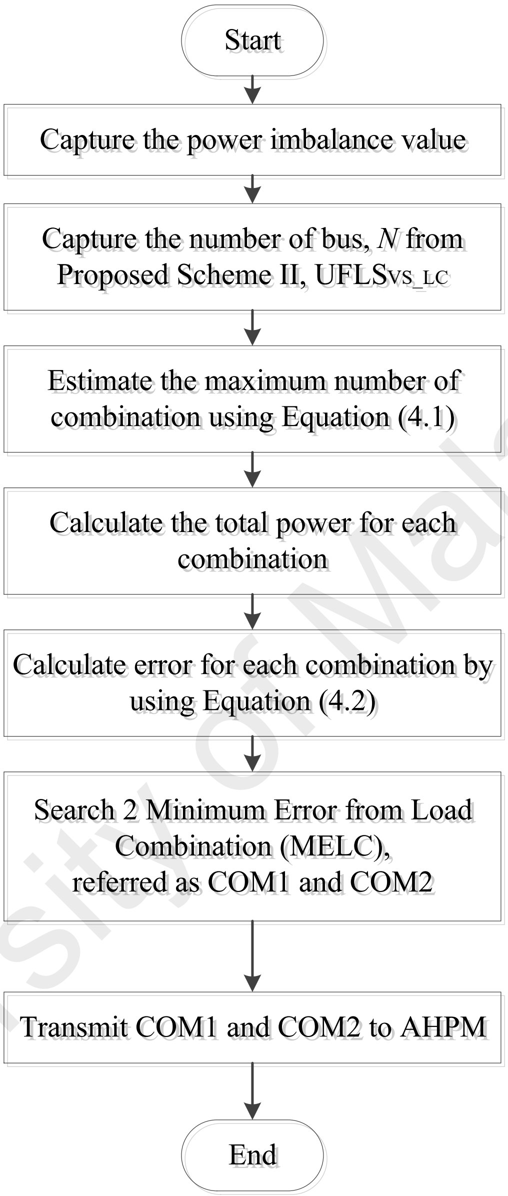


Figure 4.3: Flow chart for optimal combination of least error module

4.3.2 Analytical Hierarchy Process Module

This section details the proposed algorithms for the Analytical Hierarchy Process Module (AHPM). The decision-making process based on the AHP method is used for load selectivity. In this research, three levels of the AHP method is adopted in the decision-making process, as shown in Figure 4.4.

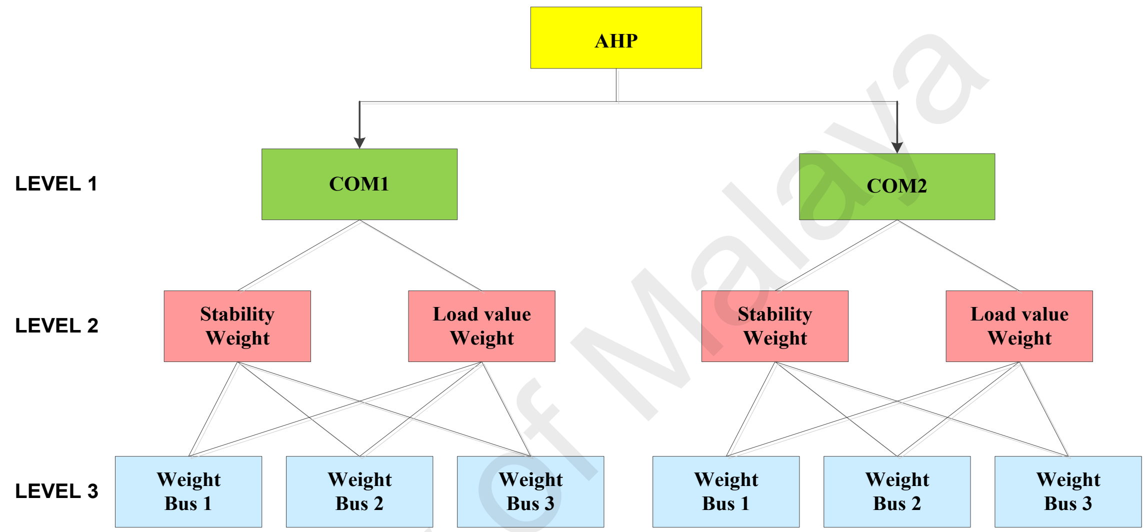


Figure 4.4: Analytical hierarchy process level

4.3.2.1 Analytical Hierarchy Process Level

For the proposed AHP method, the decision-making technique is based on the weight analysis for each level, presented as follows:

1) Level 1

At this level, the set of groups for load selection is determined. For this proposed $UFLS_{AHP}$, there are 2 groups being considered; COM1 and COM2, where both are transmitted from the proposed OCLEM. In this case, the group is referred to as COM1 and COM2.

2) Level 2

At level 2, the criteria for each group are analysed. In this proposed $UFLS_{AHP}$, there are two main criteria being considered which are:

2.1) Stability Criteria

For the stability criteria, the Voltage Stability (VS) value for each bus in COM1 and COM2 is accounted for in the AHP procedure. The VS value is captured from the VSCM, and then transmitted to the AHPM.

2.2) Load Criteria

For the load criteria, the active power load for each bus in COM1 and COM2 is accounted for in the AHP procedure. The load value is captured from VSCM, and then transmitted to the AHPM.

The total value for VS and power load value for each group is evaluated using the AHP technique to obtain the normalized weight for each criterion. The sum of the criteria weight value is "1" for each group. The calculation for the criteria weight will be explained in the following section.

3) Level 3

At this level, the bus number, known as alternative presented for each group is analysed. In the proposed $UFLS_{AHP,}$ these alternatives (Bus 1, Bus 2, and Bus 3) are represented as the load buses for COM1 and COM2. At this level, the VS and load value for each bus is evaluated using the AHP method to obtain the normalized weight for each alternative. The sum of the alternative weight value is "1" for each group. The calculation for the alternative weight will be detailed in the following section.

4.3.2.2 Analytical Hierarchy Process Calculation

This section presents the weight calculation for each level.

1) Step 1 - Develop the matrix for all of the criteria

Categorize the data into two classes: Criteria based on stability, C_S, and criteria based on load value, C_{LV}. Then, analyse the value for each criterion (stability and load value) for each bus, Ai. The Ai is the value for Cs and C_{LV} at particular buses from the set of MELC. Then, the matrix for each criterion is developed, as shown in equations (4.3) - (4.4). The sum of Ai for C_S and C_{LV} is determined by using equations (4.5) - (4.6). It should be noted that steps 1 - 4 are involved in the analysis for COM1 from the set of MELC. Hence, these steps are repeated for COM2.

$$C_S = \begin{bmatrix} C_{S\_A1} \\ C_{S\_A2} \\ .... \\ C_{S\_AN} \end{bmatrix} = \begin{bmatrix} StabilityvalueBUS1 \\ StabilityvalueBUS2 \\ .... \\ StabilityvalueBUSN \end{bmatrix} \tag{4.3}$$

$$C_{LV} = \begin{bmatrix} C_{LV\_A1} \\ C_{LV\_A2} \\ .... \\ C_{LV\_AN} \end{bmatrix} = \begin{bmatrix} LoadvalueBUS1 \\ LoadvalueBUS2 \\ .... \\ LoadvalueBUSN \end{bmatrix} \tag{4.4}$$

$$\sum C_S = \sum_{i=1}^{N} C_{S\_A_N} \tag{4.5}$$

$$\sum C_{LV} = \sum_{i=1}^{N} C_{LV\_A_N} \tag{4.6}$$

2) Step 2 – Determine the normalized weight for the criteria

In this step, the weight for each criterion is determined from the pairwise comparison of the criteria. The pairwise comparison matrix is then formed, as shown in equation (4.7):

$$PairwiseMatrix_{criteria} = \begin{array}{c} \\ S \\ LV \end{array} \begin{array}{c} \begin{array}{cc} S & LV \end{array} \\ \begin{bmatrix} 1 & \dfrac{\sum C_S}{\sum C_{LV}} \\ \dfrac{\sum C_{LV}}{\sum C_S} & 1 \end{bmatrix} \end{array} \tag{4.7}$$

From equation (4.7), the eigenvector is determined by using equation (4.8):

$$PairwiseMatrix_{criteria}{}^{2} = \begin{bmatrix} 1 & \dfrac{\sum C_S}{\sum C_{LV}} \\ \dfrac{\sum C_{LV}}{\sum C_S} & 1 \end{bmatrix} \begin{bmatrix} 1 & \dfrac{\sum C_S}{\sum C_{LV}} \\ \dfrac{\sum C_{LV}}{\sum C_S} & 1 \end{bmatrix} \tag{4.8}$$

From the results in equation (4.8), the sum of the row is determined from the results obtained by using equations (4.9) and (4.10):

$$Criteria_{row} = \begin{bmatrix} \sum row_1 \\ \sum row_2 \end{bmatrix} \tag{4.9}$$

$$SumCriteria_{row} = \sum row_1 + \sum row_2 \tag{4.10}$$

Then, the weight of the criteria is normalized by using equation (4.11):

$$WeightCriteria_{COM1} = \begin{bmatrix} \dfrac{\sum row_1}{SumCriteria_{row}} \\ \dfrac{\sum row_2}{SumCriteria_{row}} \end{bmatrix} = \begin{bmatrix} Weight_{STABILITY\_COM1} \\ Weight_{LOADVALUE\_COM1} \end{bmatrix} \tag{4.11}$$

3) Step 3 – Determine the normalized weight for the alternative

In this step, the weight for each alternative is determined from the pairwise comparison of all alternatives for each criterion. This process involves individual analysis for each criterion. For example, the pairwise comparison matrix for stability criteria is formed and formulated as in equation (4.12):

$$PairwiseMatrix_{alternative} = \begin{matrix} C_{S\_A1} \\ C_{S\_A2} \\ C_{S\_A3} \\ C_{S\_AN} \end{matrix} \overset{\begin{matrix} C_{S\_A1} & C_{S\_A2} & C_{S\_A3} & C_{S\_AN} \end{matrix}}{\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{1N} \\ a_{21} & a_{22} & a_{23} & a_{2N} \\ a_{31} & a_{32} & a_{33} & a_{3N} \\ a_{N1} & a_{N2} & a_{N3} & a_{44} \end{bmatrix}} \tag{4.12}$$

Where:

C_{S_A1}, C_{S_A2}, C_{S_A2}, C_{S_AN} = the value for stability criteria at particular bus

a_{ij} = represent the value of stability C_{S_Ai} with respect to C_{S_Aj}

From equation (4.12), the eigenvector is developed by using equation (4.13):

$$PairwiseMatrix_{alternative}{}^{2}$$

$$= \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{1N} \\ a_{21} & a_{22} & a_{23} & a_{2N} \\ a_{31} & a_{32} & a_{33} & a_{3N} \\ a_{N1} & a_{N2} & a_{N3} & a_{44} \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{1N} \\ a_{21} & a_{22} & a_{23} & a_{2N} \\ a_{31} & a_{32} & a_{33} & a_{3N} \\ a_{N1} & a_{N2} & a_{N3} & a_{44} \end{bmatrix} \tag{4.13}$$

From the results in equation (4.13), the sum of each row and its total are determined by using equations (4.14) and (4.15) respectively:

$$AlternativeStability_{row} = \begin{bmatrix} \sum row_1 \\ \sum row_2 \\ \sum row_3 \\ \sum row_N \end{bmatrix} \tag{4.14}$$

$$SumAlternativeStability_{row} = \sum row_1 + \sum row_2 + \sum row_3 + \sum row_N \tag{4.15}$$

Then, the weight of the criteria is normalized using equation (4.16).

$$WeightAlternativeStability_{COM1} = \begin{bmatrix} \dfrac{\sum row_1}{SumAlternativeStability_{row}} \\ \dfrac{\sum row_2}{SumAlternativeStability_{row}} \\ \dfrac{\sum row_3}{SumAlternativeStability_{row}} \\ \dfrac{\sum row_N}{SumAlternativeStability_{row}} \end{bmatrix} = \begin{bmatrix} Weight_{COM1\_S\_A1} \\ Weight_{COM1\_S\_A2} \\ Weight_{COM1\_S\_A3} \\ Weight_{COM1\_S\_AN} \end{bmatrix} \tag{4.16}$$

According to equation (4.16), the normalized weight is for the stability criteria. The same procedure is repeated (step 3) in order to obtain the normalized weight for load value criteria, as presented in equation (4.17):

$$WeightAlternativeLoadValue_{COM1} = \begin{bmatrix} \frac{\sum row_1}{SumAlternativeLoadValue_{row}} \\ \frac{\sum row_2}{SumAlternativeLoadValue_{row}} \\ \frac{\sum row_3}{SumAlternativeLoadValue_{row}} \\ \frac{\sum row_N}{SumAlternativeLoadValue_{row}} \end{bmatrix} = \begin{bmatrix} Weight_{COM1\_LV\_A1} \\ Weight_{COM1\_LV\_A2} \\ Weight_{COM1\_LV\_A3} \\ Weight_{COM1\_LV\_AN} \end{bmatrix} \quad (4.17)$$

4) Step 4 – Combine the normalized alternative with the normalized weight value

Finally, the normalized matrix of alternative (stability criteria and load value criteria) is multiplied with the normalized matrix of criteria. In this research, there are 2 sets of MELC. Then, the Bus Ranked According COM1 (BR_{COM1}) and Bus Ranked According COM2 (BR_{COM2}) are determined by using equation (4.18) and equation (4.19) respectively.

$$BR_{COM1} = \begin{bmatrix} Weight_{COM1\_S\_A1} & Weight_{COM1\_LV\_A1} \\ Weight_{COM1\_S\_A2} & Weight_{NCOM1\_LV\_A2} \\ Weight_{COM1\_S\_A3} & Weight_{COM1\_LV\_A3} \\ Weight_{COM1\_S\_AN} & Weight_{COM1\_LV\_AN} \end{bmatrix} \begin{pmatrix} Weight_{STABILITY\_COM1} \\ Weight_{LOADVALUE\_COM1} \end{pmatrix} \quad (4.18)$$

$$BR_{COM2} = \begin{bmatrix} Weight_{COM2\_S\_A1} & Weight_{COM2\_LV\_A1} \\ Weight_{COM2\_S\_A2} & Weight_{COM2\_LV\_A2} \\ Weight_{COM2\_S\_A3} & Weight_{COM2\_LV\_A3} \\ Weight_{COM2\_S\_AN} & Weight_{COM2\_LV\_AN} \end{bmatrix} \begin{pmatrix} Weight_{STABILITY\_COM2} \\ Weight_{LOADVALUE\_COM2} \end{pmatrix} \quad (4.19)$$

5) Step 5 – Develop the Bus Ranked according to COM1 and Bus Ranked according to COM2

Through AHP analysis, sets of Bus Ranked according to COM1 (BR_{COM1}) and Bus Ranked according to COM2 (BR_{COM2}) are obtained as follows:

$$BR_{COM1} = \begin{bmatrix} BR_{COM1\_A1} \\ BR_{COM1\_A2} \\ BR_{COM1\_A3} \\ BR_{COM1\_AN} \end{bmatrix} \quad (4.20)$$

$$BR_{COM2} = \begin{bmatrix} BR_{COM2\_A1} \\ BR_{COM2\_A2} \\ BR_{COM2\_A3} \\ BR_{COM2\_AN} \end{bmatrix} \quad (4.21)$$

The weight for each alternative is then analysed. This value is represented as a weight, which is the best solution from the balance comparison for criteria and load value stability. Then, the AHPM ranked the weight value in the Bus Ranked According AHP (BR_{AHP}), where the highest weight indicates the best solution for the alternative at a particular bus. In the case of similar alternative with two different weights from AHP decision making, the highest weight for that particular alternative will be considered, and the lowest weight will be eliminated. Then, BR_{AHP} is transmitted to the LSCM for load shedding, as shown in Figure 4.5. This figure shows the steps to determine the weight for each criterion and the alternative towards determining BR_{AHP}.

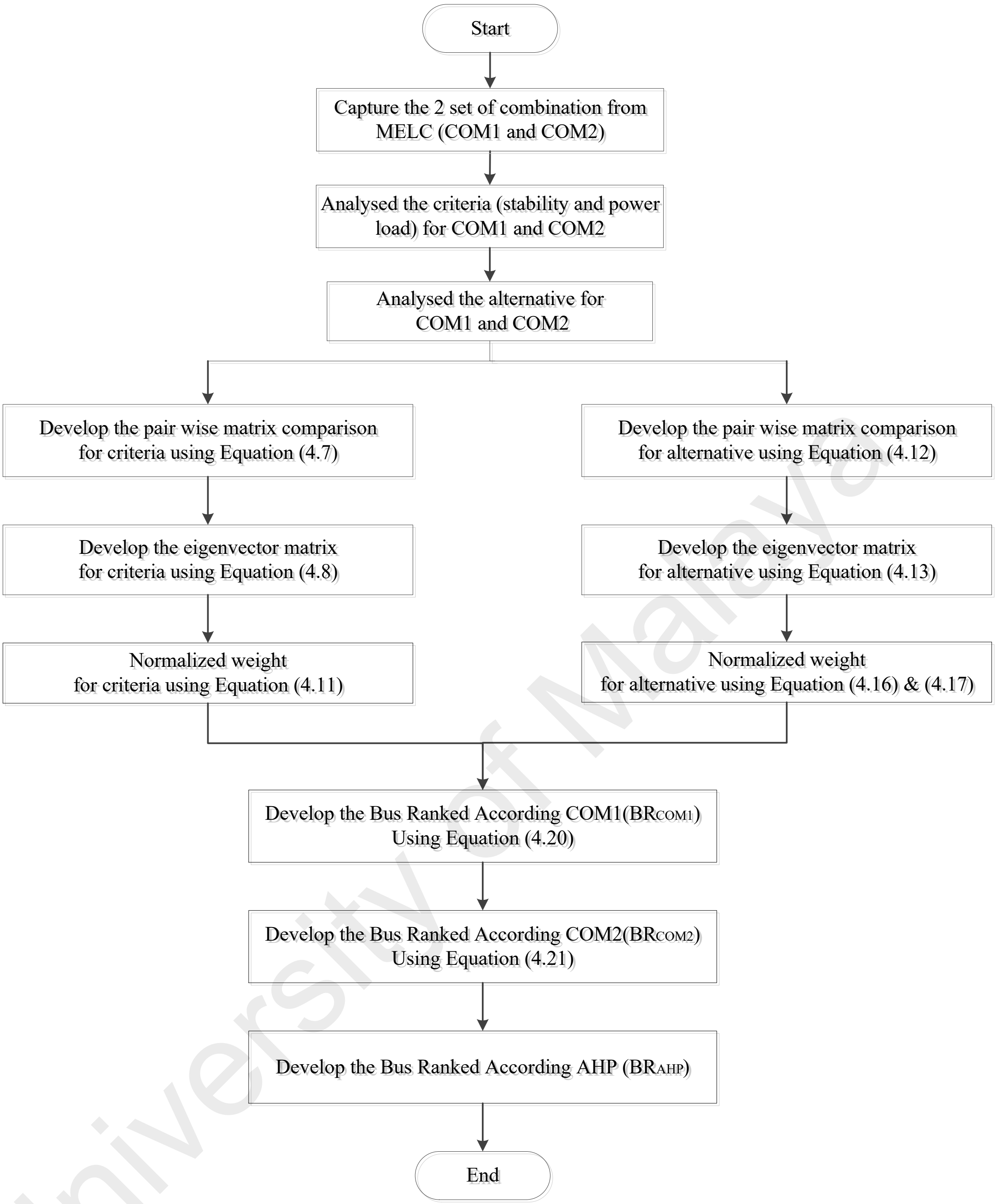


Figure 4.5: Flow chart for analytical hierarchy process module

4.3.3 Load Shedding Controller Criteria Module

The concept of the proposed algorithms for Load Shedding Controller Criteria Module (LSCCM) is similar to the proposed LSCM, detailed in Section 3.3.4. As outlined in Figure 4.6, LSCCM utilises two strategies to determine the power imbalance; event-based strategy and response-based strategy. The difference between the proposed LSCCM and the LSCM are as follows:

1) LSCCM will shed load based on BR_{AHP} from AHPM. The load is shed according to the best solution from the combination criteria from the AHPM proposed module.
2) BR_{AHP} is developed from two sets of combination of MELC, BRCOM1, and BRCOM2. The least error of load combination can ensure the realization of the optimum load shedding process.

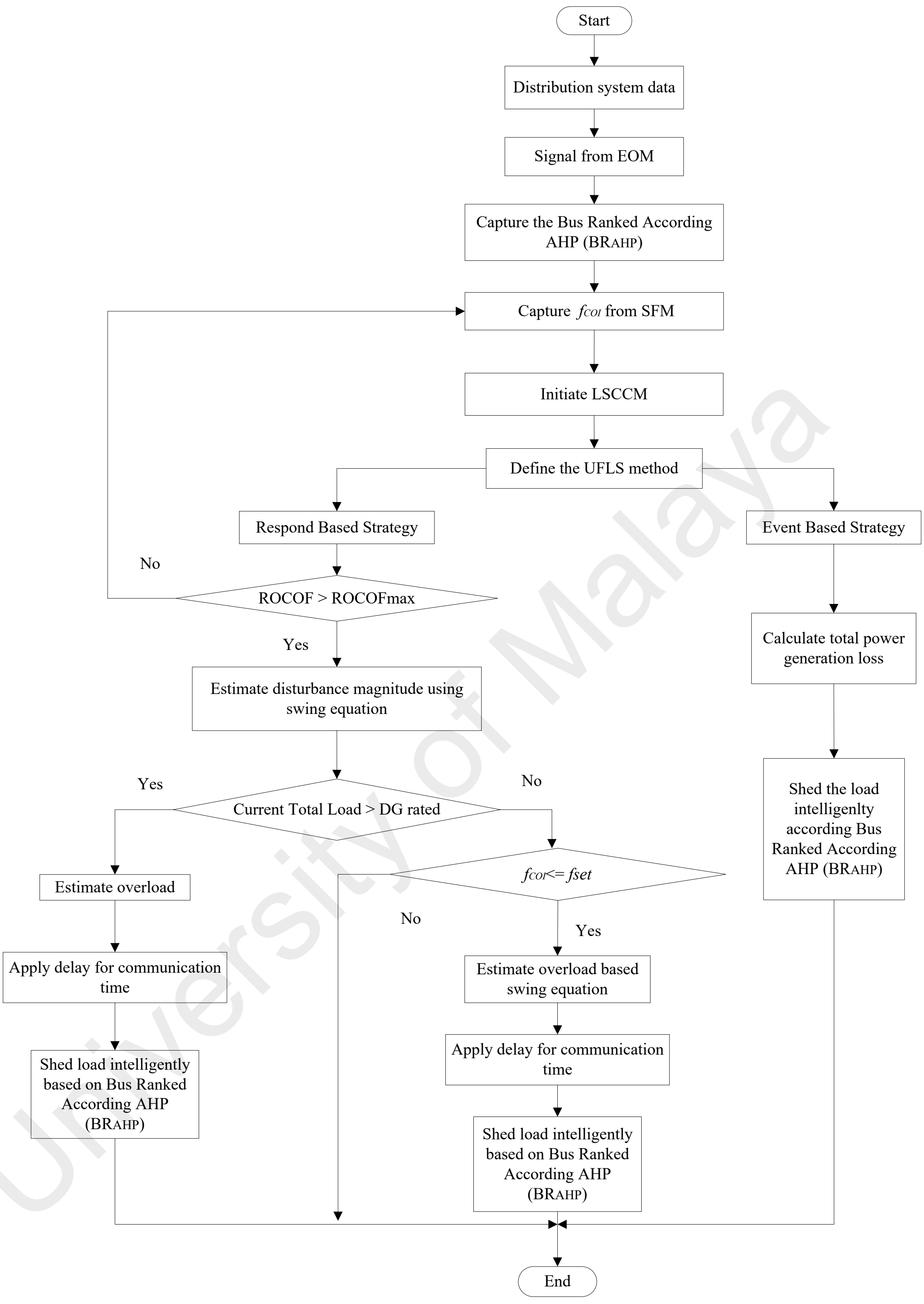


Figure 4.6: Flowchart of the proposed load shedding controller criteria module

4.4 Chapter Summary

This chapter explains the proposed $UFLS_{AHP}$ algorithm. The OCLEM algorithm is proposed in order to obtain the set of load combination possessing MELC. This will ensure that an optimal load shedding scheme is achieved in this work. Based on two sets of load combinations with MELC, the load shedding scheme based on AHPM algorithms is proposed. From this, the best of the loads is properly ranked, satisfying both criteria of stability and load value. The AHP method is adopted as the decision-making technique to consider two different criteria in load selectivity. Then, the BR_{AHP} is developed from the balance way and the pairwise comparison.

CHAPTER 5: VALIDATION OF THE PROPOSED UNDER FREQUENCY LOAD SHEDDING SCHEMES

5.1 Introduction

Chapter 4 has presented the proposed load shedding scheme based on the decision-making technique based on Analytical Hierarchy Process (AHP). This chapter deals with the validation of the proposed load shedding scheme based on Voltage Stability (VS) referred to as $UFLS_{VS}$ and the combination of VS and Load Category (LC) referred to as $UFLS_{VS\_LC}$. This chapter begins with description of practical Malaysian distribution network and corresponding generation parameters. In order to validate the effectiveness of the proposed scheme, the test system is simulated under islanded and sudden load increment cases. Through this investigation, the performance of VS index is analysed when system is grid connected, islanded and during load shedding cases.

5.2 25-Bus Test System Modelling for Proposed Under Frequency Load Shedding Scheme

Figure 5.1 shows the test system consisting of 25 buses and 20 lumped loads. At generation side, there are 2 units of Mini Hydro Synchronous Generator (MHSG) connected to the system. Each unit of MHSG is rated at capacity of 2 MVA with maximum power dispatch of 1.8 MW and operates at a voltage level of 3.3 kV. These MHSGs are connected to a 2 MVA transformers to step-up the voltage level to 11 kV. The transmission grid is connected to the distribution system via two units of step-down transformers (132 kV / 11 kV), rated 30 MVA each. The total amount for base and peak loads of the test system is 2.269 MW and 3.5872 MW, respectively.

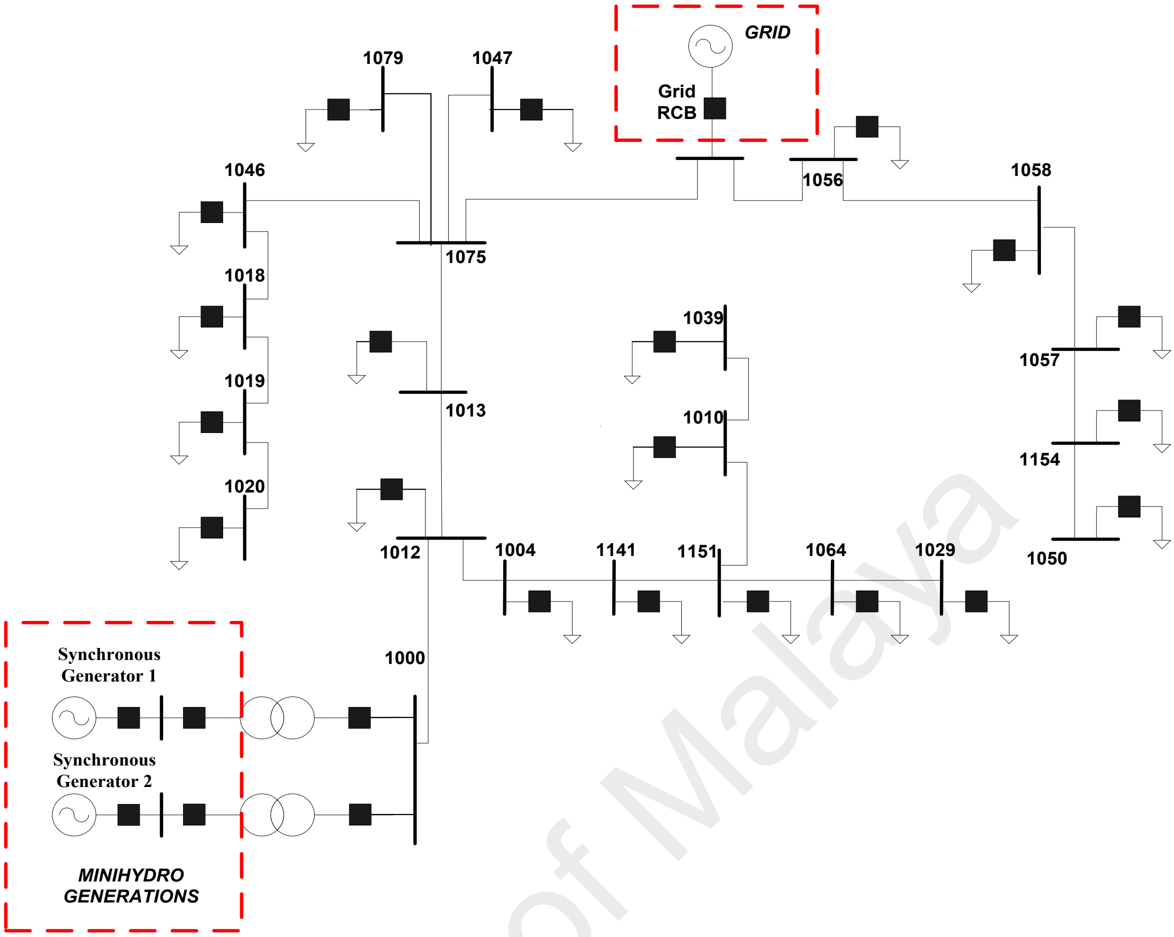


Figure 5.1: Single line diagram of the 25 bus system

The test system is modelled using PSCAD/EMTDC and the proposed algorithm is coded in Fortran Compiler. Both MHSG units' uses synchronous generators equipped with a governor, a hydraulic turbine with all the necessary valves to control water flow, and an excitation controller. To model the different mini hydro components, the exciter, the governor, and hydraulic turbine components used are based on the standard models provided in PSCAD/EMTDC library. The entire distribution line is modelled according to a nominal pi model. The islanding scenario is simulated by opening the Grid RCB (Remote Circuit Breaker). The modelling of the various components of the test system is explained in the following sections.

5.2.1 Load Modelling in Test System

In general, the load modelling in the distribution system is quite complicated because the loads are composed of different devices. For this reason, it is difficult to know the exact load composition. To address this issue, commonly, the static load model is applied in the distribution network. This type of load model considers the active and reactive power components separately as presented in equation (5.1) and (5.2):

$$P = P_O \times \left(\frac{V}{V_0}\right)^a \times \left(1 + K_{PF} \times df\right) \quad (5.1)$$

$$Q = Q_O \times \left(\frac{V}{V_0}\right)^b \times \left(1 + K_{QF} \times df\right) \quad (5.2)$$

Based on these equations, the load model is presented in algebraic function of voltage and frequency, and the real and reactive powers are represented individually. The values of exponential *a* and *b* are equal to the slope of *dp/dv* and *dq/dv* at $V = V_0$ respectively. In general, the typical range of exponential *a* value is set between 0.5 and 1.8, and for exponential *b* is set between 1.5 and 6. However, for K_{PF} and K_{QF} , the normal range is set between 0 to 3 and between -2 to 0 respectively. In this research, the model of static load is used and the parameter value is set as presented in Table 5.1.

Table 5.1: Static load parameters

Parameter	Value	Parameter	Value
a	1	K_{PF}	1
b	2	K_{QF}	-1

Table 5.2 tabulates the LC, active power and reactive power consumption at the particular bus in the test system. The loads are categorized as vital, semi-vital and non-vital. In this research, the distribution system is operated under light and peak load condition. Due to the dynamic behaviour of the system, the load value is changing throughout the simulation. Hence, the load is shed based on the frequency (reach 49.5Hz) value during system disturbances occurred. In this research, the disturbances are set at fix time (islanding operation at 3.5s and load increment at 60.0s).

Table 5.2: Total power consumption in the test system

Bus Number	Plight (MW)	Qlight (MVAR)	Ppeak (MW)	Qpeak (MVAR)	Load Category
1047	0.0464	0.0370	0.0615	0.0195	Non-vital
1013	0.0491	0.0253	0.0684	0.0423	Non-vital
1141	0.0558	0.0297	0.0796	0.0495	Non-vital
1012	0.0568	0.0297	0.0800	0.0495	Non-vital
1039	0.0581	0.0346	0.1040	0.0423	Non-vital
1050	0.0588	0.0370	0.1095	0.0576	Non-vital
1079	0.0588	0.0500	0.1179	0.0597	Non-vital
1010	0.0705	0.0500	0.1300	0.0678	Non-vital
1064	0.0804	0.0867	0.1398	0.0867	Semi-vital
1019	0.0804	0.0648	0.1601	0.0990	Vital
1151	0.0964	0.0346	0.1608	0.0996	Vital
1018	0.0967	0.1450	0.1743	0.1080	Semi-vital
1057	0.1005	0.0738	0.1890	0.1152	Non-vital
1058	0.1089	0.0765	0.1980	0.1230	Non-vital
1154	0.1215	0.0491	0.2097	0.1275	Semi-vital
1004	0.1389	0.0598	0.2121	0.1314	Semi-vital
1046	0.1621	0.1579	0.2551	0.1578	Semi-vital
1020	0.2042	0.1029	0.2767	0.1716	Semi-vital
1029	0.2548	0.1290	0.3468	0.2148	Semi-vital
1056	0.3705	0.2641	0.5139	0.3282	Vital
Total	**2.2690**	**1.5375**	**3.5872**	**2.1510**	**-**

5.2.2 Exciter Model for Synchronous Generators

The excitation system in the synchronous generators will transfer the mechanical energy to electrical energy. Consequently, the exciter model is the source of electrical energy in the synchronous generator. The exciter will regulate the generator output of voltage and reactive power. The excitation system will control the voltage and reactive power to achieve satisfactory system performance. Another function of excitation system is to provide direct current to the synchronous machine field winding. Excitation system automatically adjusts field current in order to maintain the terminal voltage. In this way, the exciter function will affect the generator's dynamic performance and impact the stability performance of the entire power system. Exciters are modelled as a dynamic transfer function in PSCAD/EMTDC software. The exciter model can be interfaced directly to the synchronous machine. The excitation system model chosen in this research is based on IEEE type AC1A standard model as shown in Figure 5.2.

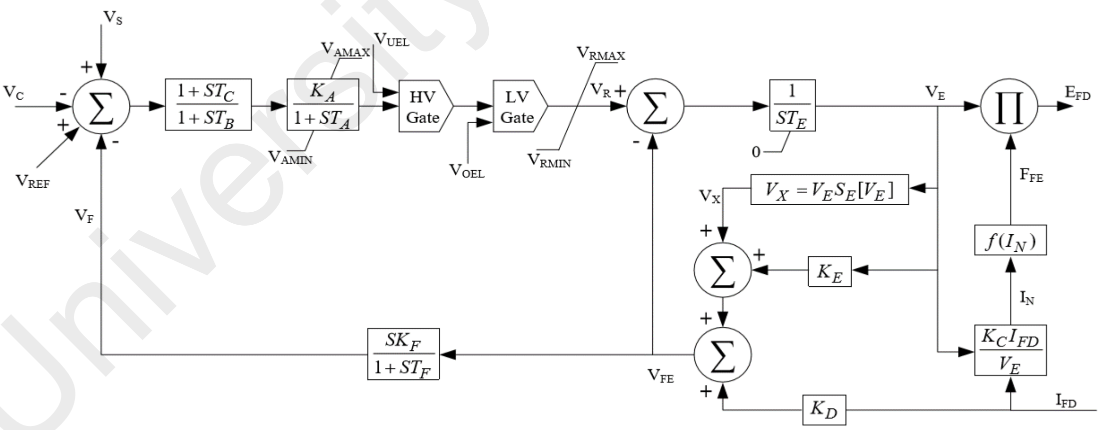


Figure 5.2: Block diagram of IEEE type AC1A excitation system model

In the excitation system model, I_{FD} is the load current's demagnetizing effect, V_E is the exciter alternator's output voltage, K_D is a constant value in the feedback path and K_C is the drop-in exciter output voltage caused by rectifier regulation. Typical parameters employed in the simulation are presented in Table 5.3.

Table 5.3: Real data of IEEE AC1A excitation model parameters

Parameter	Value	Parameter	Value
T_C	0	K_F	0.03
T_B	0	T_F	1
K_A	400	T_E	0.8
T_A	0.02	K_E	1
V_{AMAX}	14.5	K_C	0.2
V_{AMIN}	-14.5	K_D	0.38
V_{RMAX}	6.03	V_{RMIN}	-5.43
$SE(VE_1)$	0.1	$SE(VE_2)$	0.03
VE_1	4.18	VE_2	3.14

5.2.3 Hydraulic Turbine and Governor Model

Figure 5.3 shows the block diagram of hydraulic turbine and governor. The primary function of the governor is to regulate the generator's speed in order to keep the frequency at a constant value. Moreover, the governor senses speed variation and controls the turbine gate for water flow. The governor and turbine determine the mechanical torque and power applied to the generator.

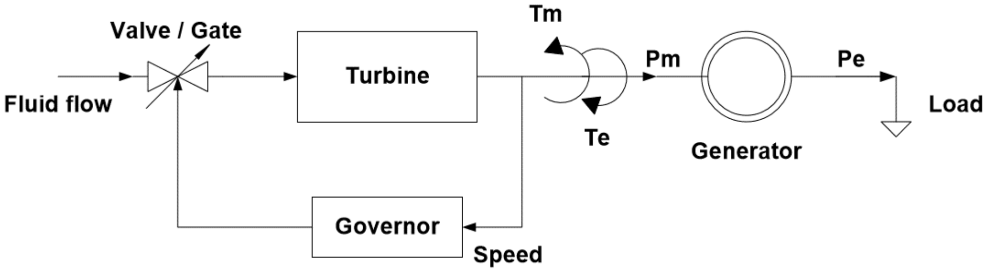


Figure 5.3: Block diagram of IEEE type AC1A excitation system model

Once there is sudden load increment or disconnection of load on the system, the turbine governor must respond promptly to avoid the over speeding of hydro turbine. During this time, the hydraulic turbine will immediately divert the water flow and close the hydraulic valve. Consequently, it is important to install and ensure the fastest response of the valve operating mechanism system. Likewise, in the situation which is posed by raising the load demand in the system, the turbine governor must respond quickly to open the hydraulic valve and avert under speeding of the hydro turbine and generator. This research employs electro-hydraulic PID governor for speed control as shown in Figure 5.4.

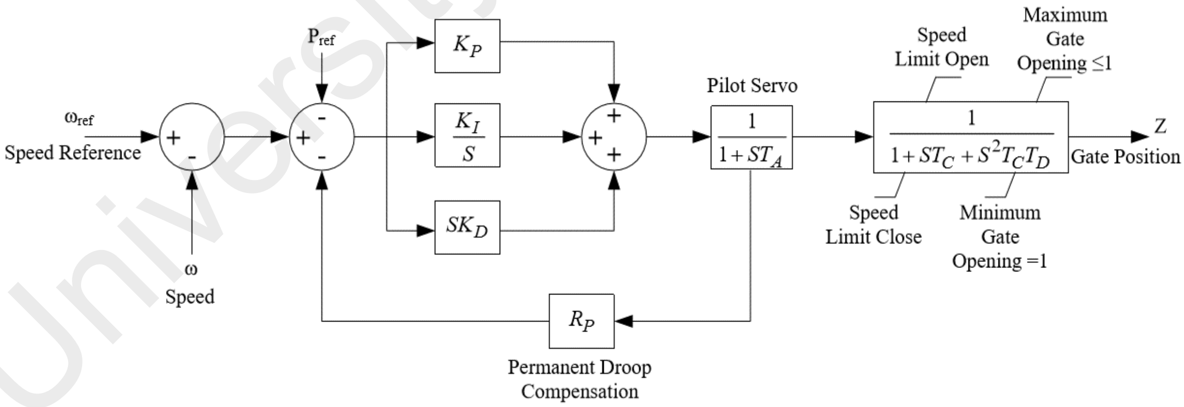


Figure 5.4: Block diagram of electro-hydraulic PID based governor

For the electro-hydraulic PID based governor model, T_A is the time constant of pilot valve and servomotor. T_C is a gate servo gain and T_D is the gate servomotor time constant. Permanent droop is shown by R_P. There are two important parameters for governor model, namely the maximum gate opening rate and maximum gate closing rate. These values are important to show the opening and closing of gate speed since the hydraulic turbine response is slower than steam or gas turbine. In this research, the parameter values employed for governor are given in Table 5.4. Nevertheless, the values for *P, I* and *D* are tuned by using trial and error method to provide satisfactory system performance.

Table 5.4: Hydraulic governor parameters

Parameter	Value	Parameter	Value
K_P	2.25	T_C	0.2
K_I	0.37	T_D	0.2
K_D	0.9	Max gate opening	0.16
T_A	0.05	Max gate closing	0.16
R_P	0.04	Dead band value	0
Max gate position	1.0	Min gate position	0

In this research, the PID parameters are tuned to obtain the match of system operation. Figure 5.5 shows the block diagram of the hydraulic turbine model. This model is nonlinear, has no surge tank and a non-elastic water column. The conduit is rigid, hence the water is incompressible fluid. The q is defined as the turbine flow prior to reduction by the reflector and relief valve. G is a gate position, f_P is the penstock head loss coefficient, A_t is the turbine gain factor, and T_w is water starting time. The T_w is varying with the load and normally its value lies between 0.5s and 4.0s.

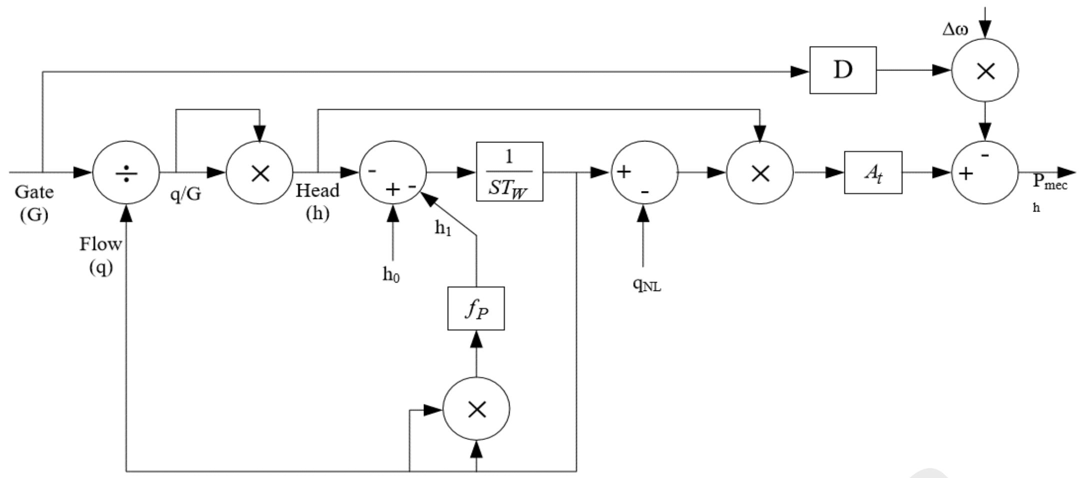


Figure 5.5: Block diagram of hydraulic turbine

Table 5.5 shows the block diagram parameters values of the hydraulic turbine model. This model provides the control action and the mechanical power which are required by the generator.

Table 5.5: Real parameters data of hydro turbine

Parameter	Value	Parameter	Value
T_W	2.25	Initial output power	0.7
f_P	0.37	Initial operating head	1.0
D	0.9	Rated output power	1.0

5.2.4 Synchronous Generator Model

In this research, two units of MHSG operate with a nominal terminal voltage of 3.3kV. These MHSG units are supplying a local load of 3.6MW and 1.4MVAR. The synchronous generator is driven by hydraulic turbine and governor control mechanism. The excitation control is an important requirement for maintaining the voltage level within permissible limits. Figure 5.6 shows the synchronous generator with PID based governor, hydraulic turbine and excitation control modelled in PSCAD.

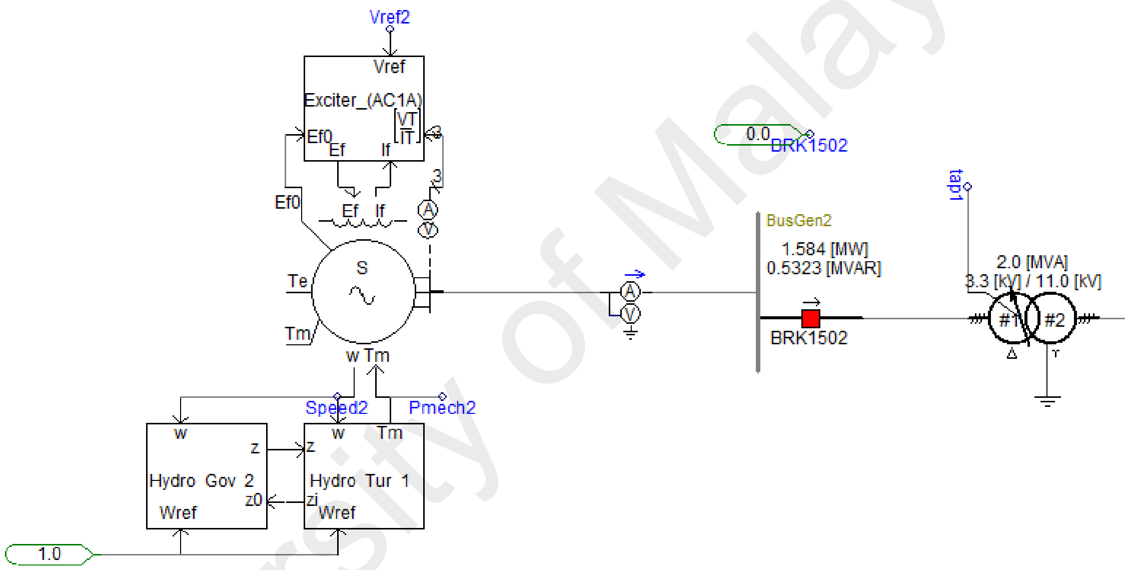


Figure 5.6: Mini hydro synchronous generator model in PCSAD/EMTDC

The synchronous generator parameters for this test system are given in Table 5.6. In this research, both MHSG units have similar specifications. In the test system, the parameters of the transformer connected to each unit of MHSG are presented in Table 5.7.

Table 5.6: Synchronous generator parameters

Parameter	Value
Rated RMS line-to-line voltage	3.3 kV
Rated RMS line current	350 A
Inertia constant (***H***)	2.5 s
Iron loss resistance	300 p.u
Base angular frequency	314.159 rad/s
Armature resistance [***Ra***]	0.01 p.u
Potier reactance [***Xp***]	0.104 p.u
Unsaturated reactance [***Xd***]	0.838 p.u
Unsaturated transient reactance [***Xd'***]	0.239 p.u
Unsaturated transient time [***Tdo'***]	8.0 s
Unsaturated sub transient reactance [***Xd''***]	0.12 p.u
Unsaturated sub transient time [***Tdo''***]	0.05 s
Unsaturated reactance [***Xq***]	0.534 p.u
Unsaturated sub transient reactance [***Xq''***]	0.12 p.u
Unsaturated transient time [***Tqo'***]	0.1 p.u
Air gap factor	1.0

Table 5.7: Transformer parameters

Parameter	Value
3-phase transformer MVA	2 MVA
Primary winding type	Delta
Secondary winding type	Star
Positive sequence leakage reactance	0.08 p.u
Air core reactance	0.2 p.u
Inrush decay time constant	1 s
Knee voltage	1.25 p.u
Magnetizing current	0.001%

5.3 Validation of the Proposed UFLS Scheme I and Proposed UFLS Scheme II

In this section, the simulation results of the proposed UFLS Scheme I are presented. The results of proposed scheme are compared with the conventional and adaptive UFLS scheme to show its effectiveness. In this research, the conventional technique is referred to as $UFLS_{CONV}$. Meanwhile, for adaptive technique is referred to as $UFLS_{ADAP}$. The modelling of $UFLS_{CONV}$ and $UFLS_{ADAP}$ scheme is also presented in this chapter. In this research, the load capacity in the system consists of light load and peak load. The total load demand for light and peak load is 2.269 MW and 3.5872 MW respectively. The test system is modelled by using PSCAD/EMTDC as shown in Figure B.1 of Appendix B.1.

In order to obtain the effectiveness of the proposed scheme, the islanded distribution network is simulated as shown in Figure 5.7. In this validation, there are two (2) main cases:

1) Case I - intentional islanding
2) Case II - load increment

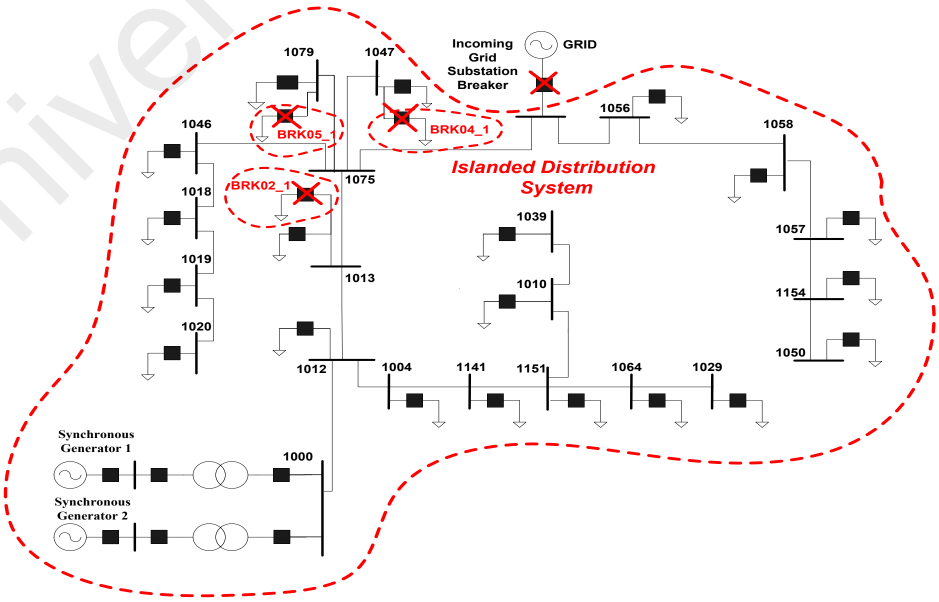


Figure 5.7: Islanded distribution system

In Case I, the distribution network is islanded by tripping the grid's breaker at *t* = 3.5s. The load shedding is performed to stabilize system frequency and voltage in the islanded distribution system.

For Case II, the sudden load increment occurs subsequently after islanding at *t* = 60s. The load is assumed to increase randomly in the islanded distribution network. In this research, the load is increased at three different locations (Bus 1075, 1047 and 1079). Table 5.8 shows the details of load value which is increased in the system.

Table 5.8: Load increment in the system for Case II

Bus name	Breaker name	Active Power (MW)
1075	BRK02_1	0.20
1047	BRK04_1	0.15
1079	BRK05_1	0.15

In this section, the analysis is carried out considering different types of VS index. Detail information about VS index is given in Section 3.3.3. The proposed algorithm of Voltage Stability Calculator Module (VSCM) monitors the VS value in each bus of the distribution network throughout the simulation process. The load is shed in accordance with the proposed load shedding algorithms as mentioned in Section 3.3 and Section 3.5 for Proposed UFLS Scheme I and Proposed UFLS Scheme II respectively.

5.4 Modelling of Conventional UFLS Scheme

The conventional UFLS technique consists of 9 stages without considering the priority of load categories as shown in Table 5.9. The $UFLS_{CONV}$ is initiated when the frequency falls below 49.5 Hz limit. The significant number of loads will be tripped at every frequency threshold in single step. According to Table 5.9, the total 9 stages of $UFLS_{CONV}$ is presented. The load is ranked according to the least amount of active load value without considering the load priority of the system. Obviously, this $UFLS_{CONV}$ approach is different compared to the adaptive and proposed technique; where the load starts to be shed when the frequency has reached the frequency threshold value.

Table 5.9: 9 Stages of conventional load shedding technique

UFLS stage	Bus number	Active Power (MW)	Frequency threshold (Hz)
1	1047	0.0615	49.5
	1013	0.0684	
	1141	0.0796	
2	1012	0.0800	49.4
	1039	0.1040	
3	1050	0.1095	49.3
	1079	0.1179	
4	1010	0.1300	49.2
	1064	0.1398	
5	1019	0.1601	49.1
	1151	0.1608	
	1018	0.1743	
6	1057	0.1890	49.0
	1058	0.1980	
7	1154	0.2097	48.9
	1004	0.2121	
8	1046	0.2551	48.8
	1020	0.2767	
9	1029	0.3468	48.7
	1056	0.5139	

5.5 Modelling of Adaptive UFLS Scheme

The modelling of adaptive UFLS technique is slightly different from the conventional UFLS approach. In this research, the adaptive UFLS technique is referred to as $UFLS_{ADAP.}$ The system controller will check whenever the frequency limit is reaches 49.5 Hz following system disturbances. After that, the controller will determine the amount of power imbalance by using swing equation. After estimating the power imbalance, the load is shed considering the priority of LC as shown in Table 5.10. As reported in (M. Karimi et al., 2012), the priority of the non-vital loads (e.g. Residential loads) are given priority to be shed rather than the vital load (e.g. Hospital, factory) .

Table 5.10: Load priority based on load category

Bus Ranking	Bus Number	Active Power (MW)	Reactive Power (MVAR)	Load Category (LC)
1	1047	0.0615	0.0195	Non-vital
2	1013	0.0684	0.0423	Non-vital
3	1141	0.0796	0.0495	Non-vital
4	1012	0.0800	0.0495	Non-vital
5	1039	0.1040	0.0423	Non-vital
6	1050	0.1095	0.0576	Non-vital
7	1079	0.1179	0.0597	Non-vital
8	1010	0.1300	0.0678	Non-vital
9	1057	0.1890	0.1152	Non-vital
10	1058	0.1980	0.1230	Non-vital
11	1064	0.1398	0.0867	Semi-vital
12	1018	0.1743	0.1080	Semi-vital
13	1154	0.2097	0.1275	Semi-vital
14	1004	0.2121	0.1314	Semi-vital
15	1046	0.2551	0.1578	Semi-vital
16	1020	0.2767	0.1716	Semi-vital
17	1029	0.3468	0.2148	Semi-vital
18	1019	0.1601	0.0990	Vital
19	1151	0.1608	0.0966	Vital
20	1056	0.5139	0.3282	Vital

5.6 Simulation Results for UFLS Scheme I

The proposed $UFLS_{VS}$ is tested for light load and peak load condition for two different cases:

1) Case I - islanding at 3.5 s
2) Case II - load increment at 60.0 s

In this research, due to the dynamic behaviour of the system, the load value is changing throughout the simulation. Hence, during system disturbances, the load will start to shed based on when the frequency is reached 49.5Hz during system disturbances.

5.6.1 Case I - Islanding Operation at 3.5 s

In this case, the distribution system is islanded at 3.5 s for light and the peak load scenario as follows:

5.6.1.1 Light Load Scenario

In this scenario, the performance of system frequency and voltage are analysed in light load. Figure 5.8 shows the power generation of MHSG during light load condition. It can be observed that the generators change their operation by reducing the amount of power dispatch from 3.173 MW to 2.38 MW to match with the total light load demand (2.2690 MW).

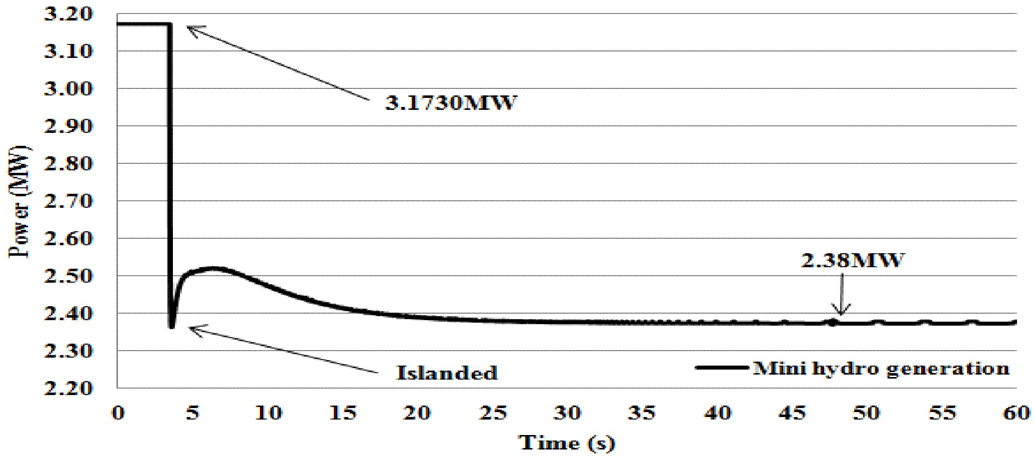


Figure 5.8: Active power generation in light load for Case I

Since the total load demand in light load scenario is within the generators capacity, the Load Shedding Controller Module (LSCM) is not activated. Load shedding is not required in this scenario. Following system islanding, the system frequency is increased to 53.2 Hz and slowly recovers to 50 Hz as shown in Figure 5.9.

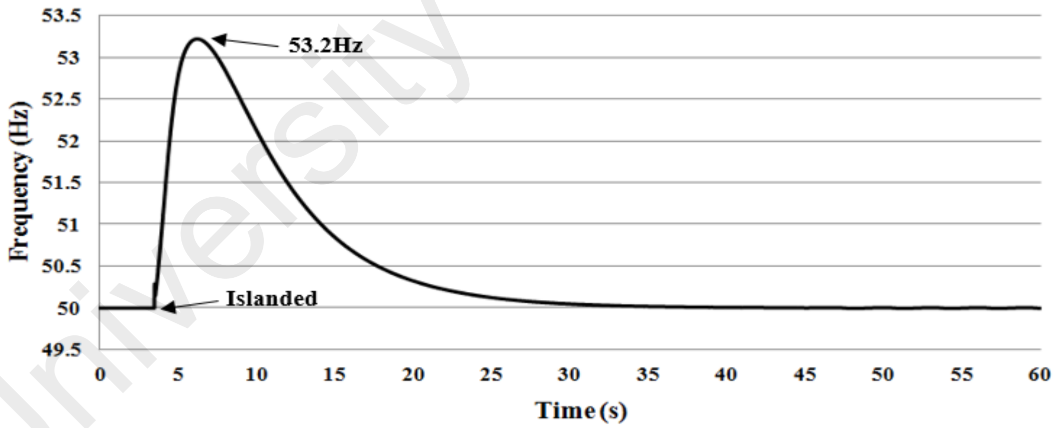


Figure 5.9: Frequency response in light load for Case I

5.6.1.2 Peak Load Scenario

Figure 5.10 shows the power generation during peak load scenario. The total power generation is 3.7079 MW, where 3.1660 MW is from the two units of MHSG and 0.5419 MW is from the grid.

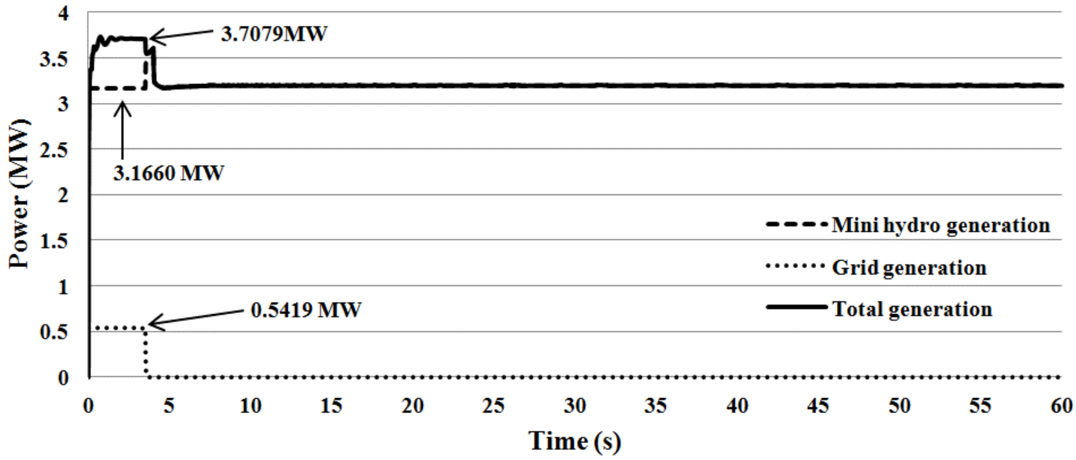


Figure 5.10: Active power generation in peak load for Case I

Following islanding, the generators have to take over the power demand which was initially supplied by the grid. Since the MHSG can only generate 3.1666 MW during system islanding, the LSCM will only initiate to shed some loads if the total load demand in the island exceeds this value.

During islanding, the system frequency decreases as shown in Figure 5.11. In order to ensure the system frequency recovers, the excess load demand in the island needs to be shed.

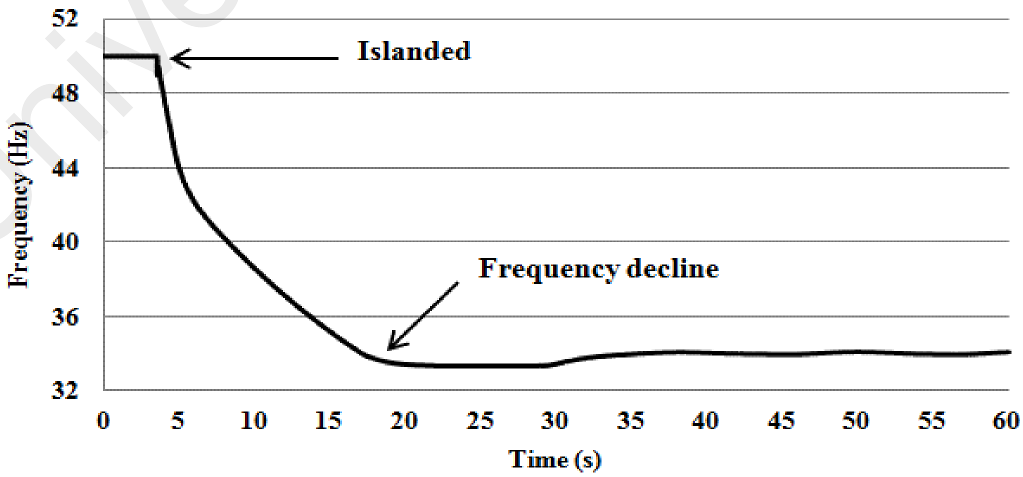


Figure 5.11: Frequency response without load shedding in peak load for Case I

Apart from system frequency decrement during islanding, the bus voltage also decreases as shown in Figure 5.12. This figure shows the voltage response for Bus 1012, 1004 and 1020. Without load shedding, the voltage magnitude value does not recover to its allowable limit.

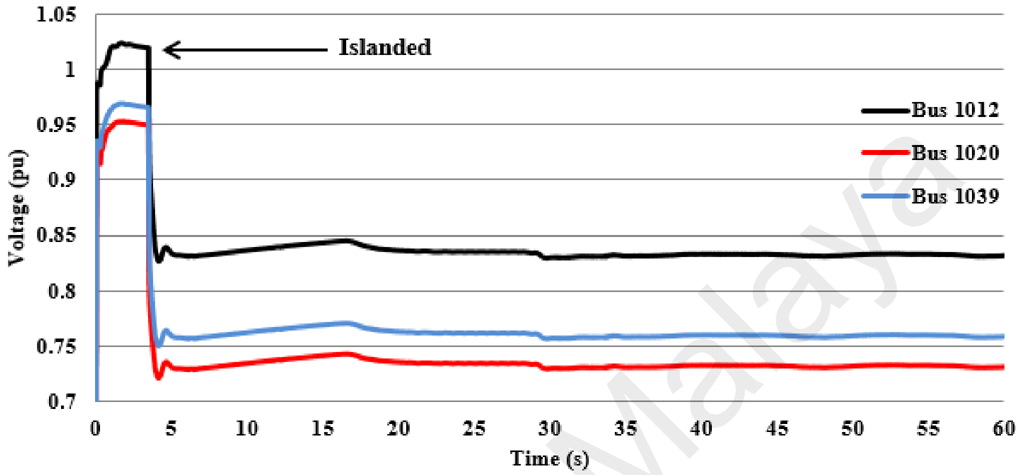


Figure 5.12: Voltage magnitude without load shedding in peak load for Case I

The VS index also changes its value following system islanding. Figure 5.13 shows the VS value SI index for Bus 1012, 1020 and 1039. Without load shedding, the VS value is not improved and can cause system collapse.

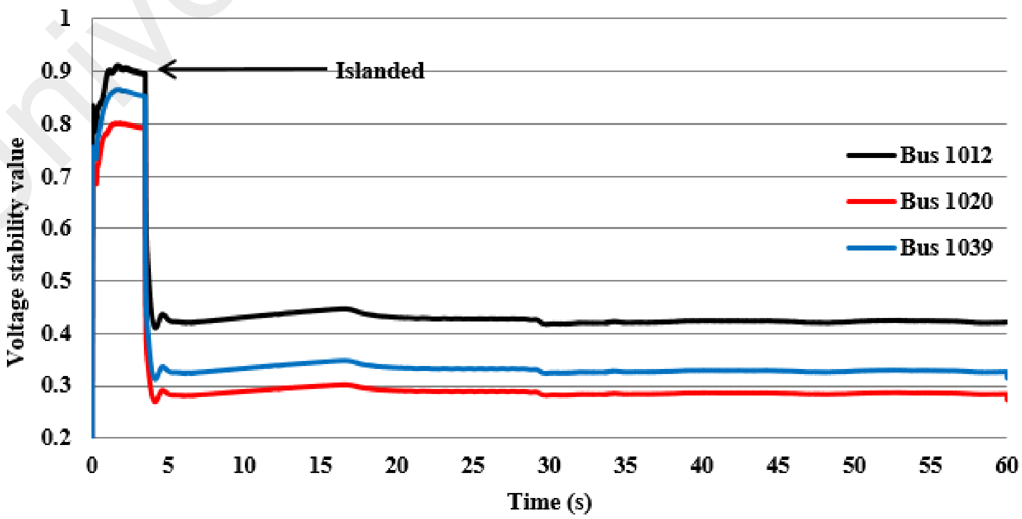


Figure 5.13: Voltage stability value without load shedding in peak load for Case I

Figure 5.14 shows the voltage magnitude response for Bus 1012, 1004 and 1020 after load shedding. It can be clearly observed that the $UFLS_{VS}$ successfully recovers the voltage magnitude after being subjected to disturbances.

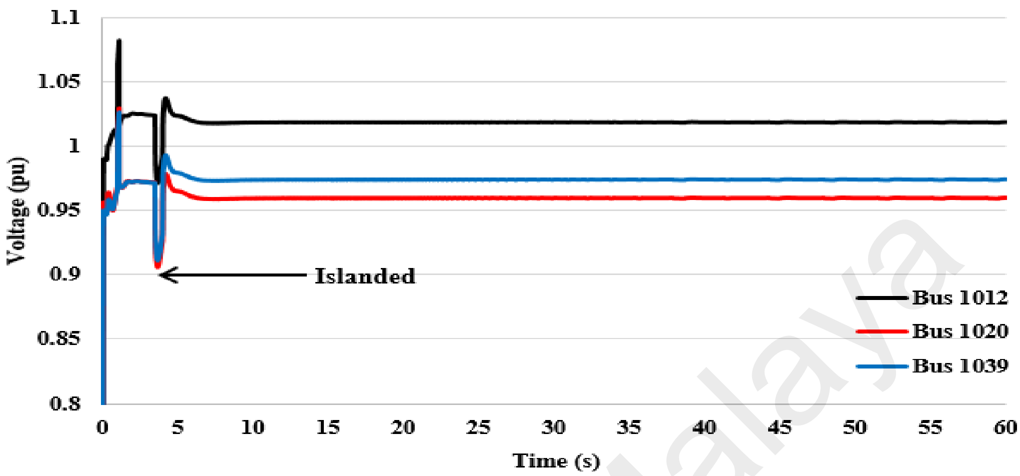


Figure 5.14: Voltage magnitude with load shedding in peak load for Case I

For the proposed $UFLS_{VS}$, the value of VS is recorded throughout the simulation process. The proposed VSCM algorithms will calculate and record the VS value for each bus continuously. Hence, the overall performance of system stability can be evaluated through the VS value. Example of VS value based on SI value is shown in Figure 5.15 for Bus 1012, 1020 and 1039.

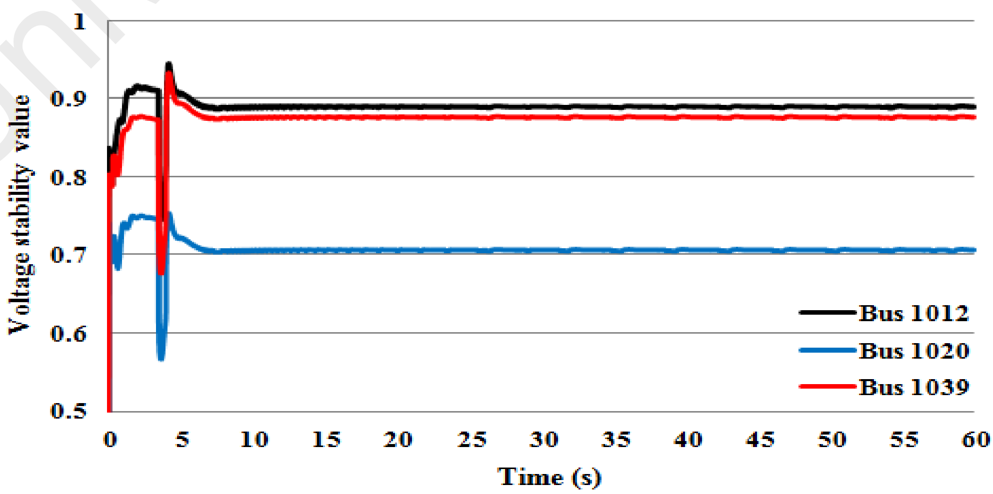


Figure 5.15: Voltage stability value with load shedding in peak load for Case I

The analysis for SI ranking is presented in Table 5.11. Table 5.11(a) presents the SI value during grid connected and system islanding. Meanwhile Table 5.11(b) presents the SI value after load shedding. From these two tables, it can be seen that there are changes of bus ranking after load shedding (based on the index value, lower to higher). For example, before load shedding (Table 5.11(a)), Bus 1029 (SI value = 0.4559) and Bus 1051 (SI value = 0.5569) are ranked 1st and 2nd respectively. However, when load shedding occurs at these two buses, their ranking now changes to 18th position (SI value = 0.8958) and 19th position (SI value = 0.9063) respectively as shown in Table 5.11(b). This indicates that their VS value has improved. Should be noted that the analysis for other indices are presented in Table B.1- B.6 of Appendix B.2.

Table 5.11: Analysis for bus ranked SI value

(a) SI value for grid connected and islanding

$\mathbf{BR_{VS}}$	$\mathbf{SI_{grid\ connected}}$	$\mathbf{SI_{islanded}}$
1029	0.5752	0.4559
1151	0.7054	0.5569
1020	0.7482	0.5741
1056	0.8074	0.6162
1004	0.8279	0.6384
1047	0.8368	0.6384
1057	0.8452	0.6433
1154	0.8577	0.6522
1018	0.8594	0.6572
1019	0.8603	0.6575
1046	0.8674	0.6636
1064	0.8695	0.6805
1010	0.8738	0.6838
1039	0.8753	0.6847
1050	0.881	0.6692
1058	0.8869	0.6743
1079	0.9026	0.6895
1141	0.9035	0.709
1012	0.9112	0.7529
1013	0.9512	0.7463

(b) SI value after load shedding

$\mathbf{BR_{VS}}$	$\mathbf{SI_{loadshed}}$
1020	0.7072
1056	0.7601
1047	0.7902
1057	0.795
1004	0.8012
1154	0.8065
1018	0.812
1019	0.8127
1046	0.8197
1050	0.8282
1058	0.834
1079	0.8526
1064	0.8718
1010	0.8762
1039	0.8777
1141	0.8817
1012	0.8908
1029	0.8958
1151	0.9063
1013	0.9205

0 = critical 1 = stable

In order to see the overall system performance during grid connected, islanding and after load shedding, the SI value and voltage magnitude at all buses are plotted in a form of a spider-web chart, shown in Figure 5.16. From this figure, it can be seen that when system is islanded, both SI value and voltage magnitude drops from high values (blue line) to lower values (red line). When load shedding is initiated, it can be seen that these values improved significantly as indicated by the green line.

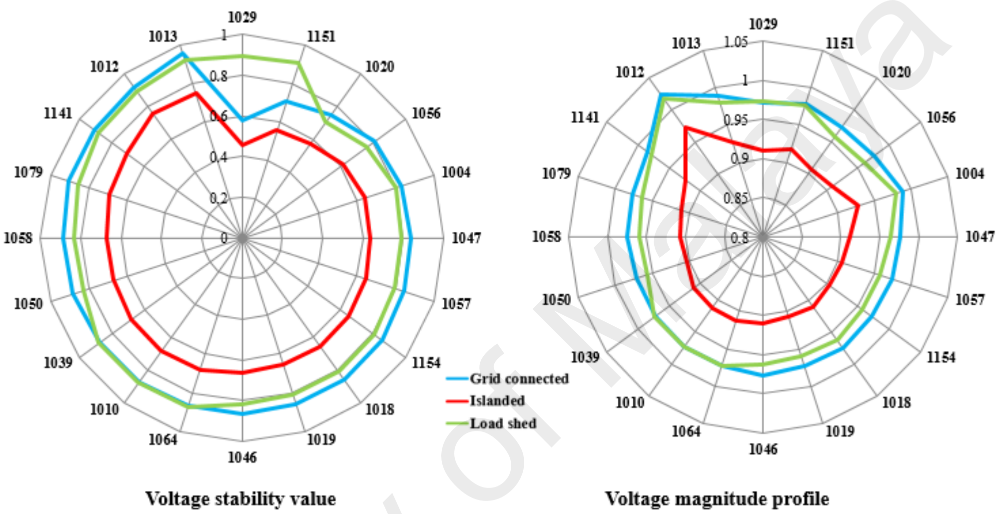


Figure 5.16: Comparison of voltage stability and voltage magnitude for SI

Similar analysis is repeated using other voltage stability indices; VSI, PSI, FVSI, NLSI, Lp and Lmn. The comparison between VS and voltage magnitude profile for all index are presented in Figure 5.17 to Figure 5.22. However, it should be noted, for these indices the index value that is close to “1” indicates critical condition and close to “0” indicates stable condition.

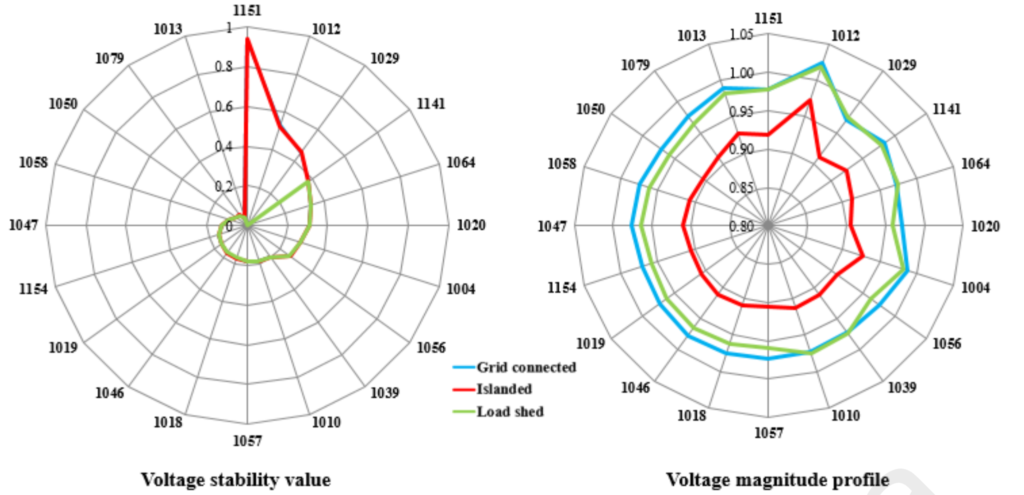


Figure 5.17: Comparison of voltage stability and voltage magnitude for VSI

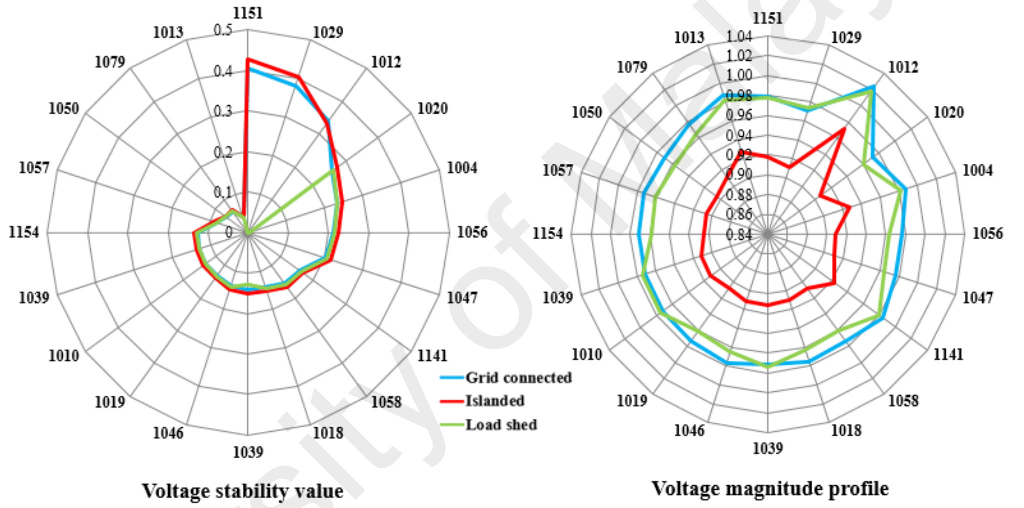


Figure 5.18: Comparison of voltage stability and voltage magnitude for PSI

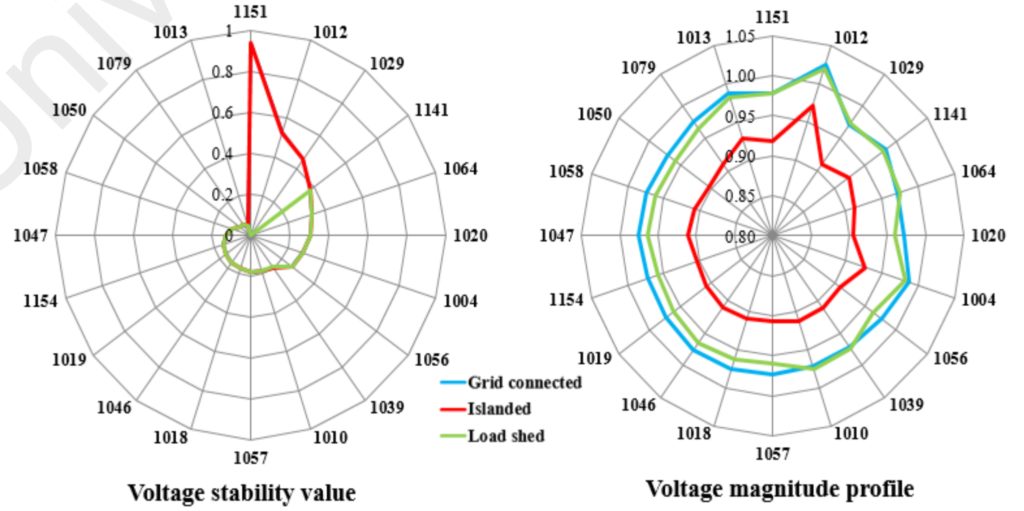


Figure 5.19: Comparison of voltage stability and voltage magnitude for FVSI

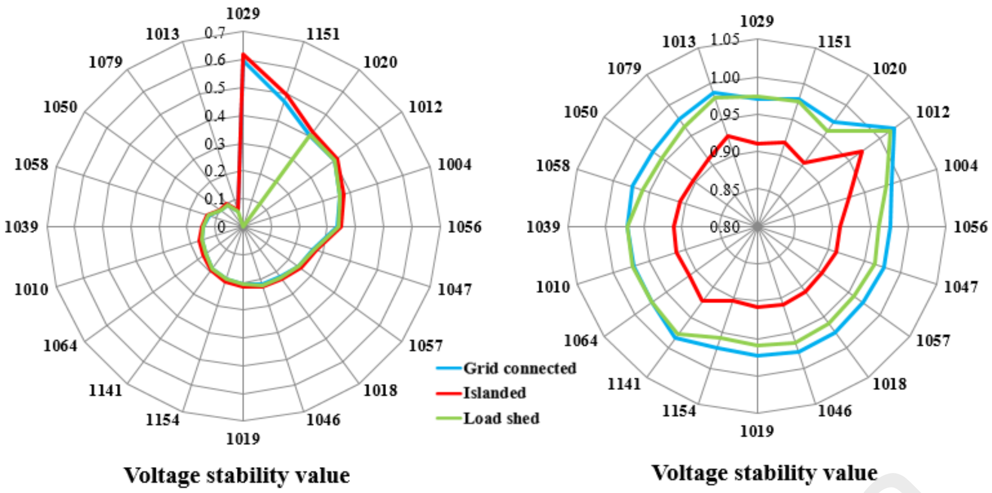


Figure 5.20: Comparison of voltage stability and voltage magnitude for NLSI

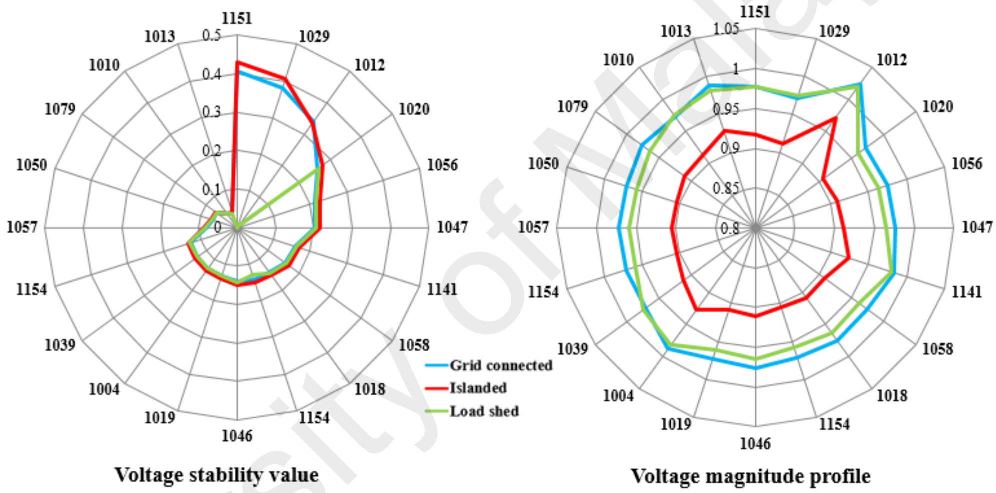


Figure 5.21: Comparison of voltage stability and voltage magnitude for Lp

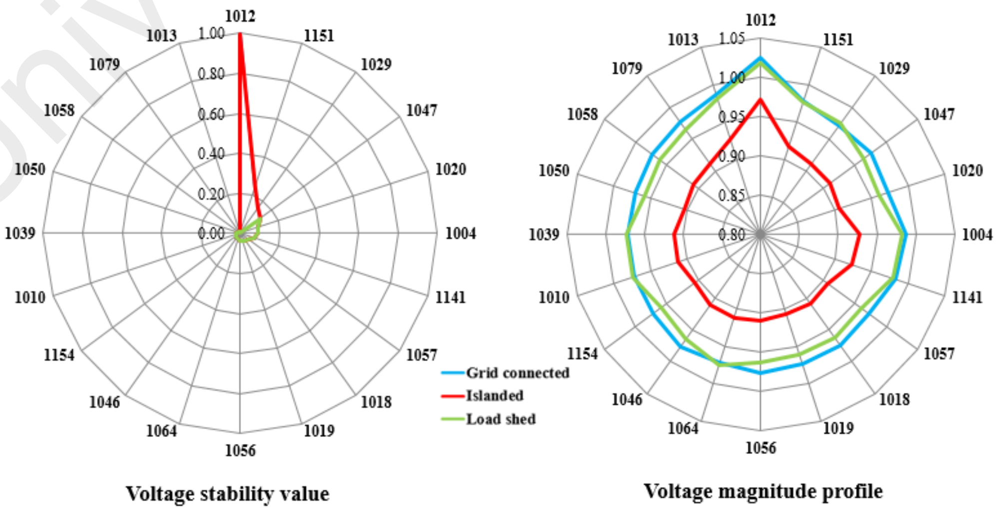


Figure 5.22: Comparison of voltage stability and voltage magnitude for Lmn

The overall performance of voltage magnitude is illustrated in Figure 5.23. It can be clearly noticed that proposed $UFLS_{VS}$ shows the highest voltage magnitude improvement compared to $UFLS_{CONV}$ and $UFLS_{ADAP}$. For proposed $UFLS_{VS}$, SI and NLSI index shows the same voltage magnitude. Also, the similar pattern for VSI, PSI, FVSI, Lp and Lmn index is observed. Out of 20 buses, 19 buses improved its voltage magnitude, which is 95% improvement from all buses in the network. The value for voltage profile is presented in Table B.7 of Appendix B.3.

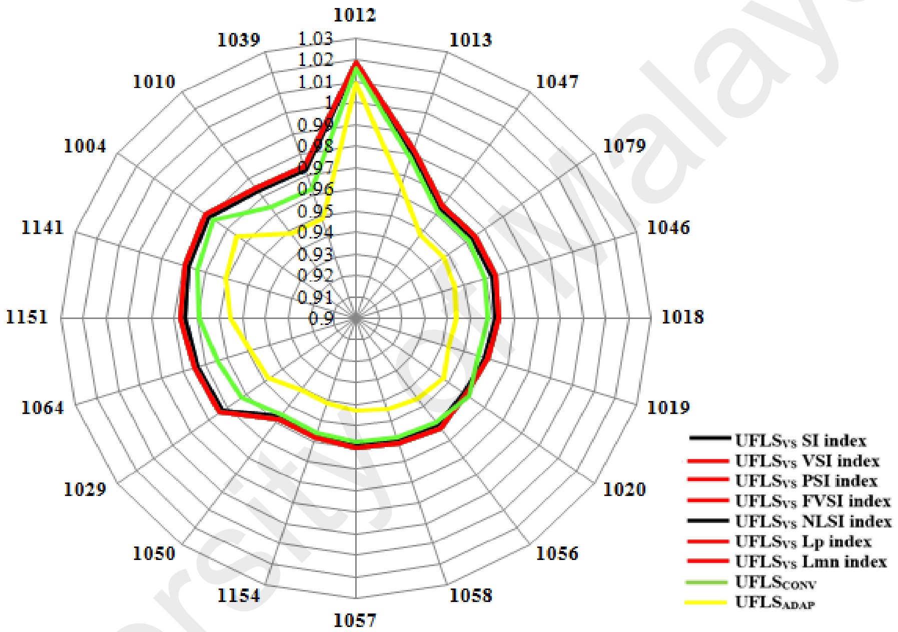


Figure 5.23: Voltage magnitude profile in peak load for Case I

Figure 5.24 shows the comparison of frequency responses for proposed $UFLS_{VS}$, $UFLS_{CONV}$ and $UFLS_{ADAP}$ scheme. The $UFLS_{CONV}$ and $UFLS_{ADAP}$ techniques show higher overshoot of 50.7 Hz and 50.3 Hz respectively compared to the $UFLS_{VS}$. It may be noted that the $UFLS_{CONV}$ caused the frequency to decrease to 49.2 Hz in the system.

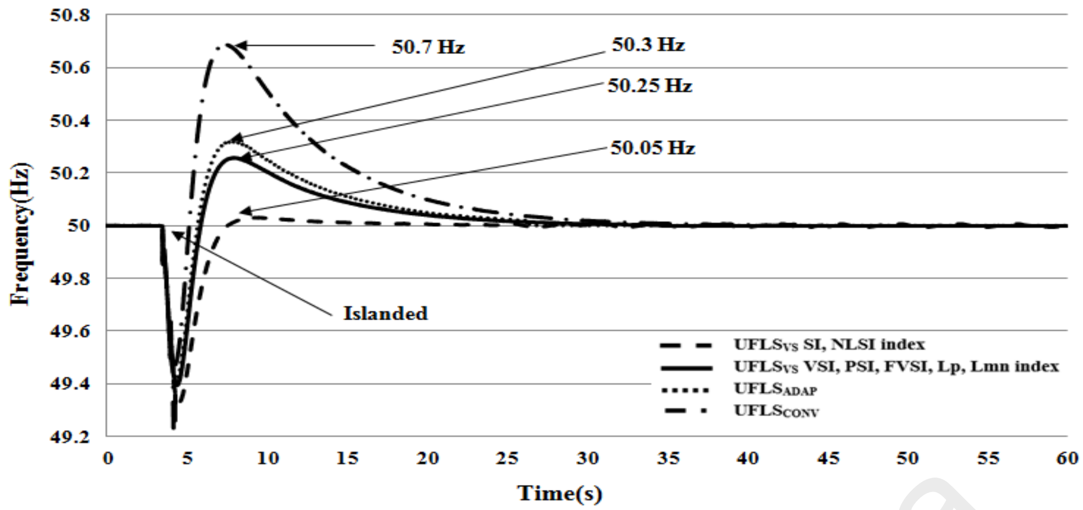


Figure 5.24: Comparison of frequency responses in peak load for Case I

The total amount shed for $UFLS_{VS}$, $UFLS_{CONV}$ and $UFLS_{ADAP}$ is tabulated in Table 5.12. From this table, the total amount shed for $UFLS_{CONV}$ and $UFLS_{ADAP}$ is 0.7509 MW and 0.6209 MW respectively which exceeds the power imbalance value (0.54 MW). Meanwhile, the proposed $UFLS_{VS}$ shows that an appropriate amount of load has been shed in the system. For SI and NLSI index, 0.5076 MW has been shed in the system. However, for VSI, PSI, FVSI, Lp and Lmn index, the load shed amount is 0.5876 MW.

Although some improvement in voltage and frequency is observed from this proposed $UFLS_{VS}$, some issues were observed when the vital load (Bus 1151) is selected to be shed. Hence, the $UFLS_{VS\_LC}$ is introduced in UFLS Scheme II, by considering the LC and VS simultaneously in the proposed scheme.

Table 5.12: Analysis for bus number and total shed amount in peak load for Case I

Bus number		1012	1013	1047	1079	1046	1018	1019	1020	1056	1058	1057	1154	1050	1029	1064	1151	1141	1004	1010	1039	**Total shed amount (MW)**
Load category		Non-vital	Non-vital	Non-vital	Non-vital	Semi-vital	Semi-vital	Vital	Semi-vital	Vital	Non-vital	Non-vital	Semi-vital	Non-vital	Semi-vital	Semi-vital	Vital	Non-vital	Semi-vital	Non-vital	Non-vital	
Techniques																						
UFLSVS	**SI**														√		√					0.5076
	VSI	√													√		√					0.5876
	PSI	√													√		√					0.5876
	FVSI	√													√		√					0.5876
	NLSI														√		√					0.5076
	Lp	√													√		√					0.5876
	Lmn	√													√		√					0.5876
UFLSADAP		√	√	√	√									√				√			√	0.6209
UFLSCONV		√	√	√	√									√				√		√	√	0.7509

5.6.2 Case II - Load Increment in the System at 60 s

In this case, sudden load increments occur at 60.0 s for light and the peak load scenario as follows.

5.6.2.1 Light Load Scenario

In order to secure the system operation, the LSCM initiated the response-based strategy to prevent further decline of system frequency. In this case, the magnitude of disturbance is estimated with regards to the overload value in the system. The total load on the island is 2.6032 MW for light load scenario.

Following an overload, the LSCM is initiated when Rate of Change of Frequency (ROCOF) is greater than ROCOFmax. The total load is increased to 3.7793 MW. However, due to load increment, the MHSG increased its generation to 2.87 MW as shown in Figure 5.25.

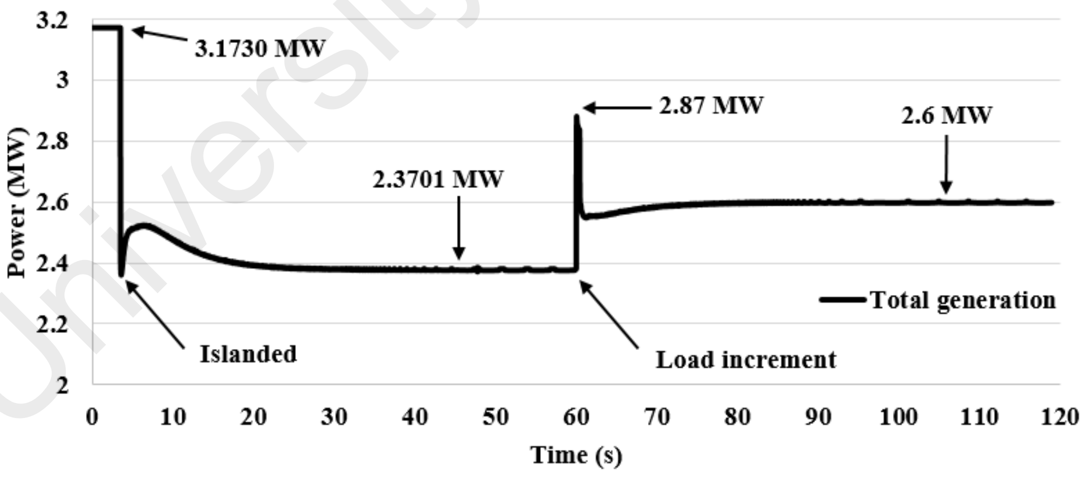


Figure 5.25: Active power generation in light load for Case II

The analysis for SI ranking is presented in Table 5.13. Table 5.13(a) presents the SI value when system is islanded. Meanwhile Table 5.13(b) presents the SI value for load increment and after load shedding. From these two tables, it can be seen that there are changes of bus ranking due to sudden load increment in the system (based on the index value, lowest to highest). For example, during system islanding (Table 5.13(a)), Bus 1047 (SI index = 0.8707) is at 4^{th} position in the BR_{VS}. However, when sudden load increment occurs in the system, its ranking now changes to 2^{nd} position in BR_{VS} (SI value = 0.6951) in Table 5.13(b). Also, there are changes in VS value after load shedding (based on the index value, lowest to highest). For example, during load increment (Table 5.13(b)), the SI value for Bus 1012 and Bus 1047 are 0.6034 and 0.6951 respectively. After load shedding, these values have increased to 1.1069 and 1.1082 for Bus 1012 and 1047 respectively. This indicates that their VS value has improved. Should be noted that the analysis for other indices are presented in Table B.8 - B.13 of Appendix B.4.

Table 5.13: Analysis for bus ranked SI value

(a) SI value during islanding

BR_{VS}	$SI_{islanded}$
1012	0.6906
1029	0.7714
1020	0.8471
1047	0.8707
1056	0.8722
1151	0.8883
1018	0.8964
1057	0.9062
1046	0.9088
1154	0.9102
1019	0.9132
1050	0.9163
1058	0.9205
1064	0.9251
1004	0.9289
1039	0.9310
1079	0.9311
1010	0.9312
1141	0.9505
1013	0.9753

(b) SI value for load increment and after load shedding

BR_{VS}	$SI_{load\ increment}$	$SI_{load\ shed}$
1012	0.6034	1.1069
1047	0.6951	1.1082
1029	0.7128	0.7683
1020	0.7743	0.8383
1056	0.7975	0.8632
1018	0.8194	0.8873
1151	0.8200	0.8854
1057	0.8278	0.8970
1079	0.8288	0.9003
1046	0.8305	0.8995
1154	0.8311	0.9009
1019	0.8341	0.9040
1050	0.8367	0.9071
1058	0.8406	0.9112
1064	0.8532	0.9222
1004	0.8575	0.9258
1039	0.8585	0.9280
1010	0.8588	0.9283
1013	0.8667	0.9403
1141	0.8770	0.9476

0 = critical 1 = stable

Figure 5.26 shows the overall system performance for SI value. From this figure, it can be seen that when sudden load increased, both VS value and voltage magnitude drops from higher values (red line) to lower values (brown line). When load shedding is initiated, it can be seen that these values are improved as indicated by the green line.

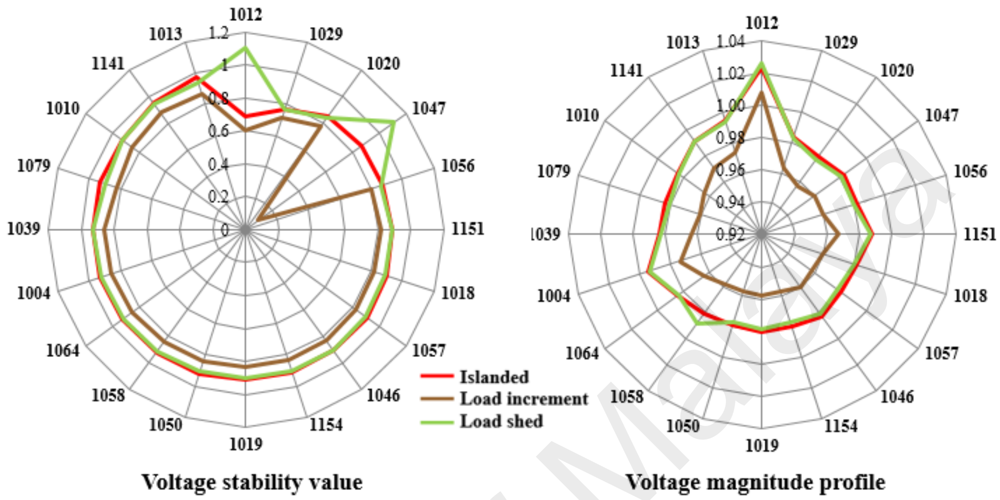


Figure 5.26: Comparison of voltage stability and voltage magnitude for SI

Similar analysis is repeated by using other voltage stability indices; VSI, PSI, FVSI, NLSI, Lp and Lmn. The comparison between VS and voltage magnitude profile for all index are presented in Figure 5.27 to Figure 5.32. For these indices, the index value that are close to “1” indicates critical condition, while close to “0” indicates stable condition.

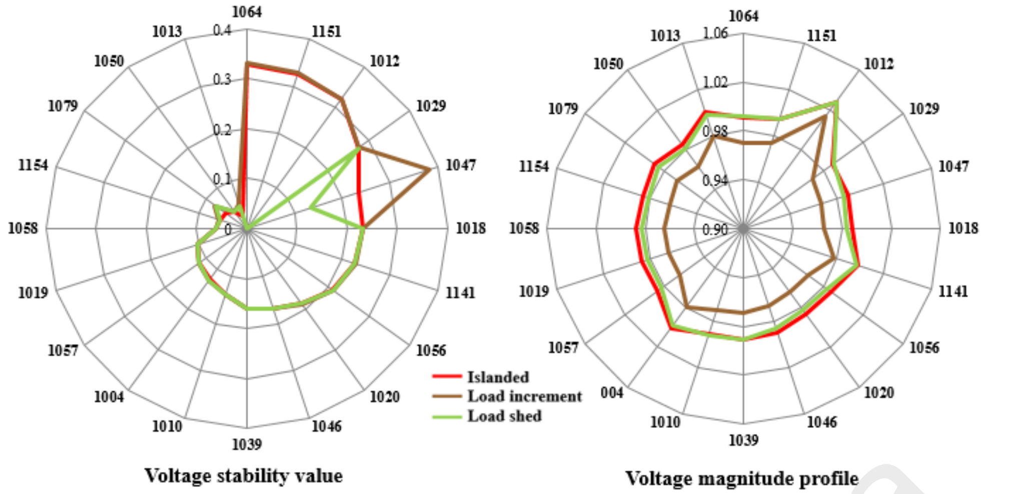


Figure 5.27: Comparison of voltage stability and voltage magnitude for VSI

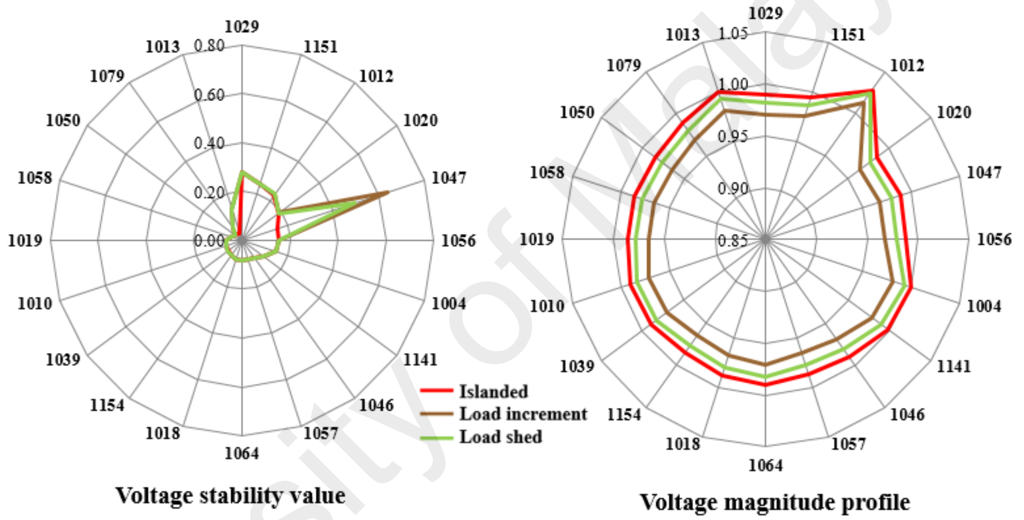


Figure 5.28: Comparison of voltage stability and voltage magnitude for PSI

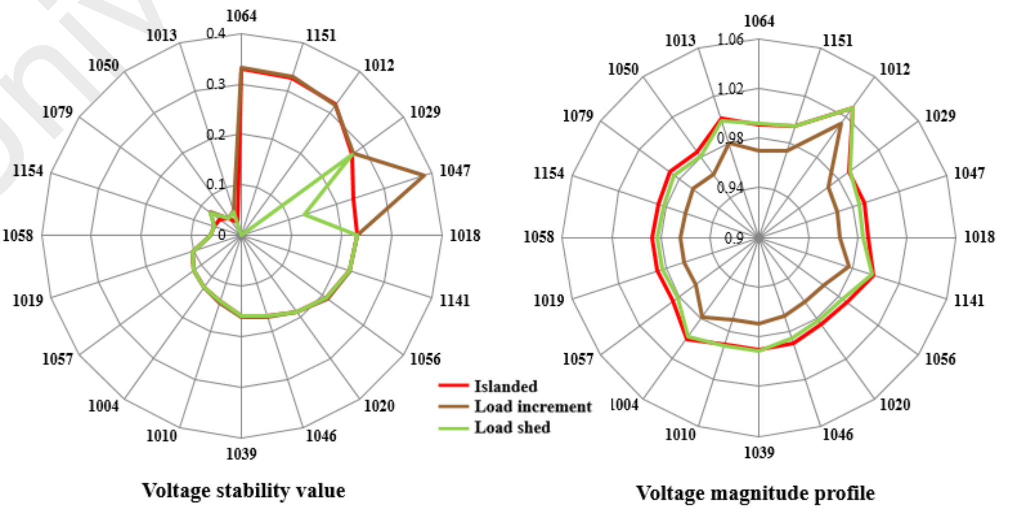
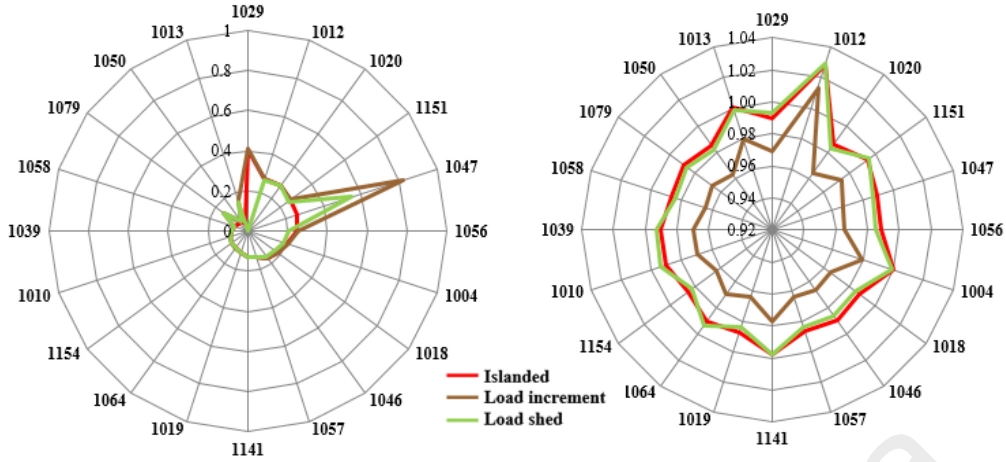


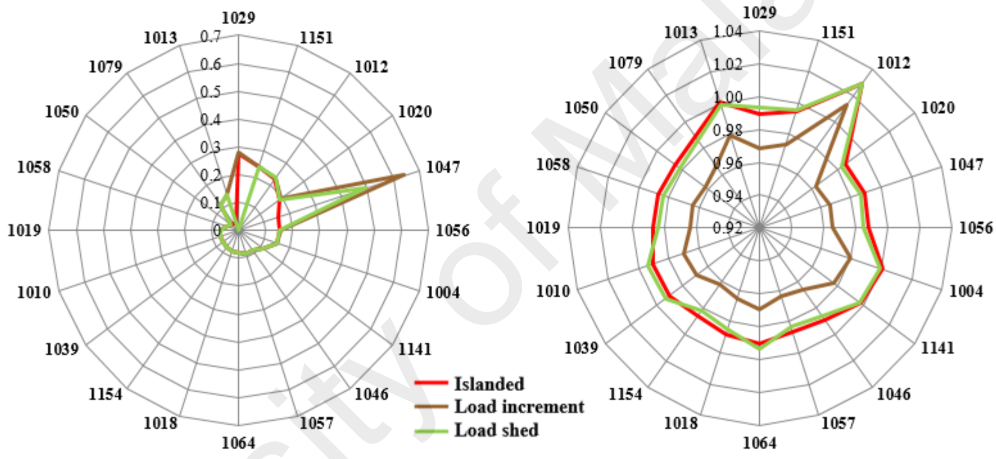
Figure 5.29: Comparison of voltage stability and voltage magnitude for FVSI



Voltage stability value

Voltage magnitude profile

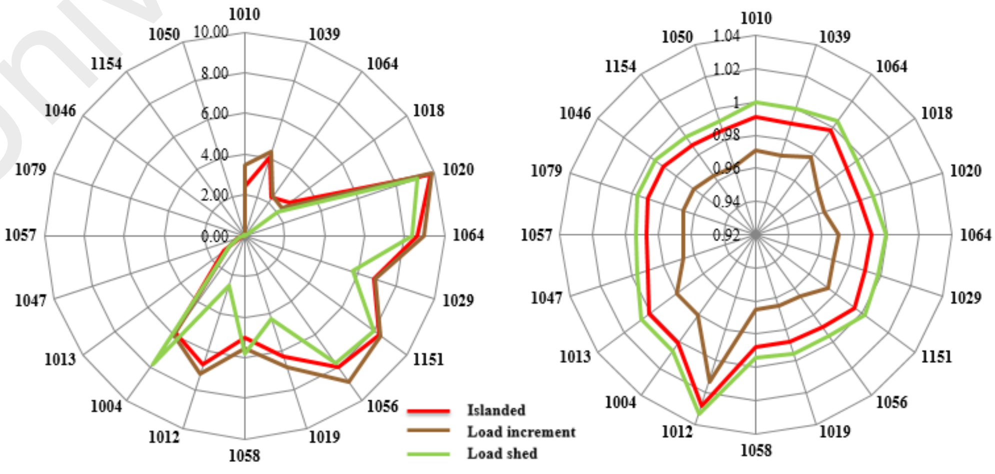
Figure 5.30: Comparison of voltage stability and voltage magnitude for NLSI



Voltage stability value

Voltage magnitude profile

Figure 5.31: Comparison of voltage stability and voltage magnitude for Lp



Voltage stability value

Voltage magnitude profile

Figure 5.32: Comparison of voltage stability and voltage magnitude for Lmn

The overall performance of voltage magnitude is illustrated in Figure 5.33. It can be noticed that the proposed $UFLS_{VS}$ shows the highest voltage magnitude improvement compared to $UFLS_{CONV}$ and $UFLS_{ADAP}$. For proposed $UFLS_{VS}$, Lp and NLSI index shows same voltage magnitude values with similar pattern for VSI, and FVSI. Based on proposed $UFLS_{VS}$, Lmn index shows 100% of voltage magnitude improvement for all buses compared to other indices. The value for voltage profile is presented in Table B.14 of Appendix B.5.

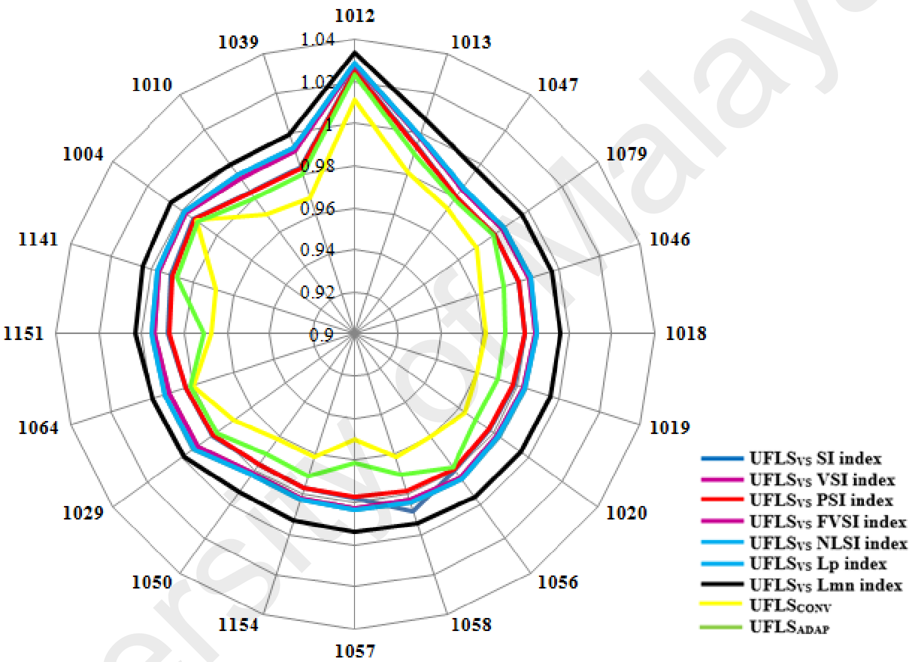


Figure 5.33: Voltage magnitude profilein light load for Case II

Figure 5.34 illustrates the comparison of frequency performance for $UFLS_{VS}$, $UFLS_{ADAP}$ and $UFLS_{CONV}$. In this figure, the $UFLS_{CONV}$ suffers further decline in system frequency compared to $UFLS_{ADAP}$ and $UFLS_{VS}$. For $UFLS_{CONV}$, the frequency will decrease until 48.5 Hz before it recovers to 50 Hz. Also, it takes a significant amount of time to successfully recover the system frequency compared to $UFLS_{VS}$. For $UFLS_{VS}$, the Lmn index shows fast recovery of system frequency compared to other indices.

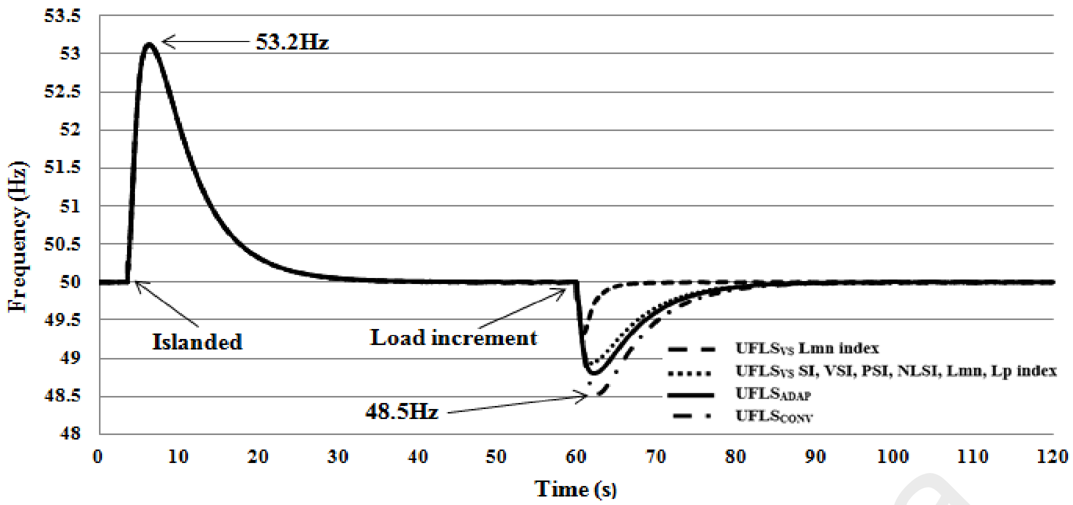


Figure 5.34: Comparison of frequency responses in light load for Case II

Table 5.14 shows the total load shed for $UFLS_{CONV}$, $UFLS_{ADAP}$ and $UFLS_{VS}$. The $UFLS_{CONV}$ shed shows that highest amount of load is shed due to load increment in the system compared to other load shedding schemes. In this case, Bus 1047 which is involved with sudden load increment is involved in load shedding process. The $UFLS_{VS}$ successfully updates the BR_{VS} upon system disturbances. This enhances the effectiveness of the proposed $UFLS_{VS}$, where the load increment can cause certain bus (eg: Bus 1047) to approach unstable condition. Furthermore, in case of VSI and FVSI, the vital load of Bus 1151 is involved in load shedding.

Table 5.14: Analysis for bus number and total shed amount in light load for Case II

Bus number		1012	1013	1047	1079	1046	1018	1019	1020	1056	1058	1057	1154	1050	1029	1064	1151	1141	1004	1010	1039	Total shed amount (MW)
Load category		Non-vital	Non-vital	Non-vital	Non-vital	Semi-vital	Semi-vital	Vital	Semi-vital	Vital	Non-vital	Non-vital	Semi-vital	Non-vital	Semi-vital	Semi-vital	Vital	Non-vital	Semi-vital	Non-vital	Non-vital	
Techniques																						
UFLS$_{VS}$	**SI**	√		√																		0.2532
	VSI	√		√												√	√					0.4300
	PSI			√																		0.1964
	FVSI	√		√												√	√					0.4300
	NLSI			√											√							0.4512
	Lp			√											√							0.4512
	Lmn															√				√	√	0.2090
UFLS$_{ADAP}$		√	√	√										√				√			√	0.4750
UFLS$_{CONV}$		√					√							√	√	√		√		√		0.6738

5.6.2.2 Peak Load Scenario

Figure 5.35 shows the total power generation in the system prior to sudden load increment in the system. During system islanding, the MHSG is supplying 3.166 MW. However, due to sudden load increment of 0.5 MW, the total generation increases to 3.666 MW, which exceeds the maximum capacity of both MHSG generation (3.6 MW). The LSCM is initiated when the ROCOF is greater than ROCOFmax.

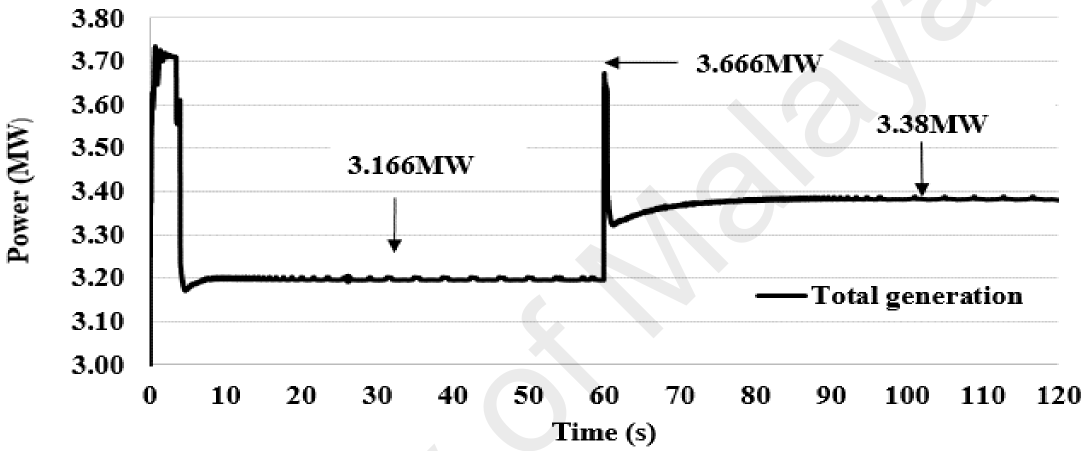


Figure 5.35: Active power generation in peak load for Case II

The analysis for SI value ranking is presented in Table 5.15. Table 5.15(a) presents the SI value when system islanding. Meanwhile Table 5.15(b) presents the SI value for load increment and after load shedding. From these two tables, it can be seen that there are changes of bus ranking due to sudden load increment in the system (based on the index value, lowest to highest). For example, during system islanding (Table 5.15(a)), Bus 1047 (SI value = 0.7902) is at 3rd position in the BR_{VS}. However, when sudden load increment occurs in the system, its ranking is changes to 1st position 1 in BR_{VS} (SI value = 0.5304) in Table 5.15(b). Also, there are changes of VS value after load shedding (based on the index value, smaller to higher). For example, during load increment (Table 5.15(b)), the SI value for Bus 1047 and Bus 1020 are 0.5304 and 0.6691 respectively. After load shedding, these values have increased to 0.5892 and 0.7200 for Bus 1047 and 1020 respectively. This indicates that their VS value has improved. Should be noted that the analysis for other indices are presented in Table B.15 - B.20 of Appendix B.6.

Table 5.15: Analysis for bus ranked SI value

(a) SI value during islanding

BR$_{VS}$	**SI$_{islanded}$**
1020	0.7072
1056	0.7601
1047	0.7902
1057	0.7950
1004	0.8012
1154	0.8065
1018	0.8120
1019	0.8127
1046	0.8197
1050	0.8282
1058	0.8340
1079	0.8526
1064	0.8718
1010	0.8762
1039	0.8777
1141	0.8817
1012	0.8908
1029	0.8958
1151	0.9063
1013	0.9205

(b) SI value for load increment and after load shedding

BR$_{VS}$	**SI$_{load\ increment}$**	**SI$_{load\ shed}$**
1047	0.5304	0.5892
1020	0.6691	0.7200
1056	0.7187	0.7595
1057	0.7509	0.7947
1154	0.7616	0.8062
1004	0.7620	0.7985
1018	0.7670	0.8135
1019	0.7675	0.8172
1046	0.7743	0.8191
1050	0.7818	0.8279
1058	0.7874	0.8337
1079	0.7953	0.8243
1064	0.8276	0.8696
1010	0.8318	0.8741
1039	0.8331	0.8755
1141	0.8373	0.8794
1029	0.8958	0.9032
1151	0.9063	0.9700
1012	0.8609	0.8907
1013	0.8637	0.8841

0 = critical 1 = stable

Figure 5.36 shows the overall system performance for SI value. From this figure, it can be seen that when load increment occurs, both VS value and voltage magnitude dropped from higher values (red line) to lower values (brown line). After load shedding, it can be seen that these values improved as indicated by the green line.

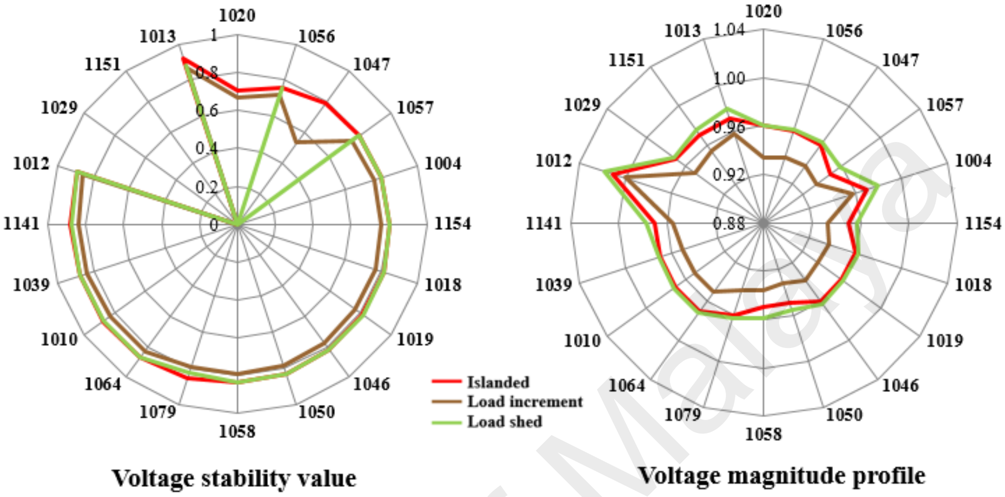


Figure 5.36: Comparison of voltage stability and voltage magnitude for SI

Similar analysis is repeated by using other voltage stability indices; VSI, PSI, FVSI, NLSI, Lp and Lmn. The comparison between VS and voltage magnitude profile for all index are presented in Figure 5.37 to Figure 5.42. However, it should be noted, for these indices the index value that is close to "1" indicates critical condition and close to "0" indicates stable condition.

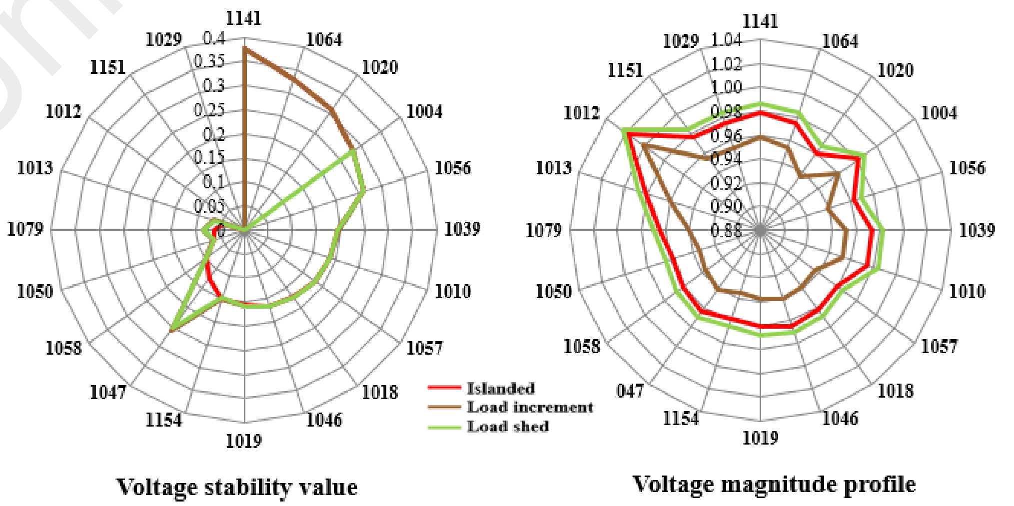


Figure 5.37: Comparison of voltage stability and voltage magnitude for VSI

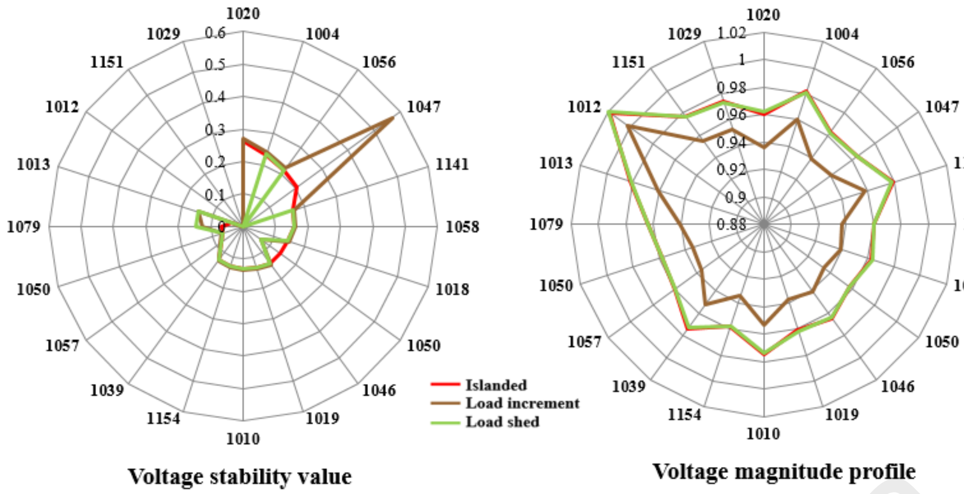


Figure 5.38: Comparison of voltage stability and voltage magnitude for PSI

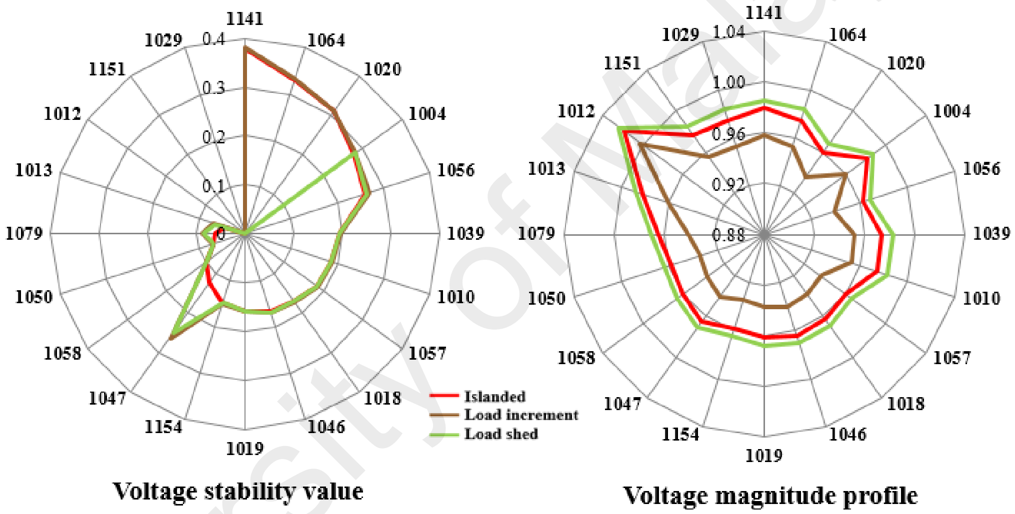


Figure 5.39: Comparison of voltage stability and voltage magnitude for FVSI

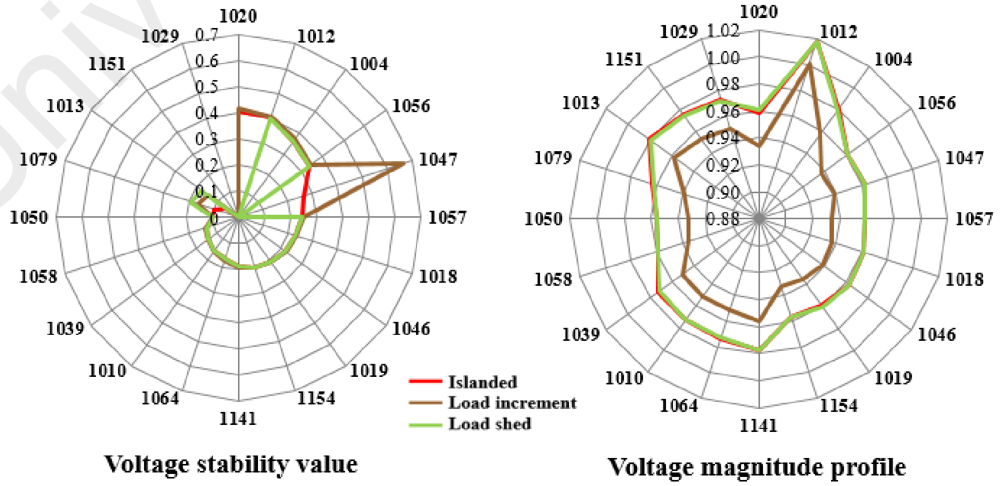


Figure 5.40: Comparison of voltage stability and voltage magnitude for NLSI

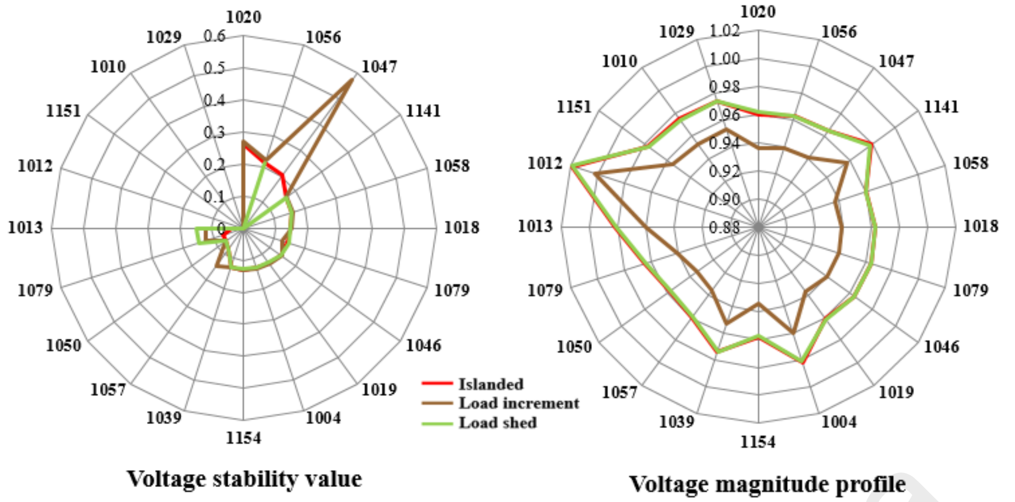


Figure 5.41: Comparison of voltage stability and voltage magnitude for Lp

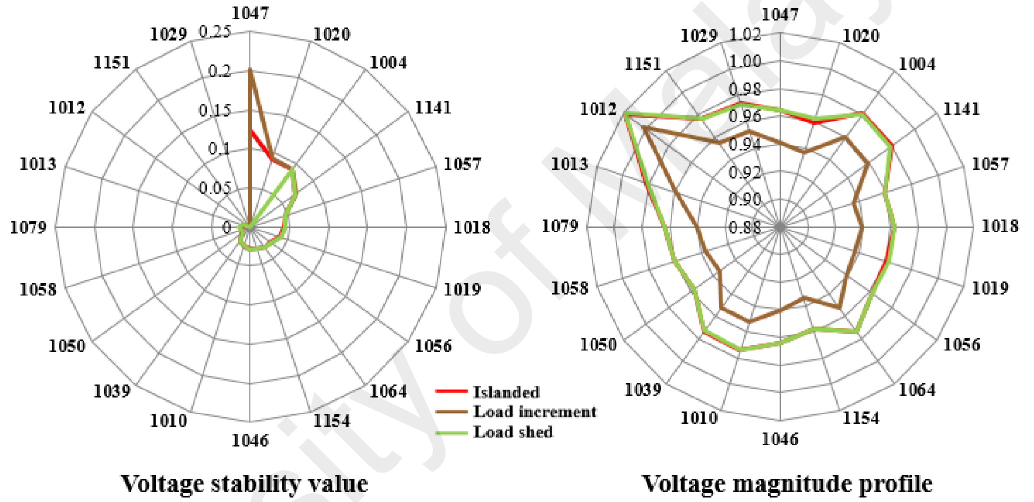


Figure 5.42: Comparison of voltage stability and voltage magnitude for Lmn

The overall performance of voltage magnitude is illustrated in Figure 5.43. It can be noticed that the proposed $UFLS_{VS}$ show the highest voltage magnitude improvement compared to $UFLS_{CONV}$ and $UFLS_{ADAP}$. For $UFLS_{VS}$, VSI and FVSI index shows the same voltage magnitude value. Also, similar pattern for Lp, Lmn and PSI can be observed. From $UFLS_{VS}$, VSI and FVSI index shows significant improvement in voltage magnitude compared to other indices. It may be further noted that the voltage magnitude of all buses in the system is improved 100%. The value of voltage magnitude profile is presented in Table B.21 of Appendix B.7.

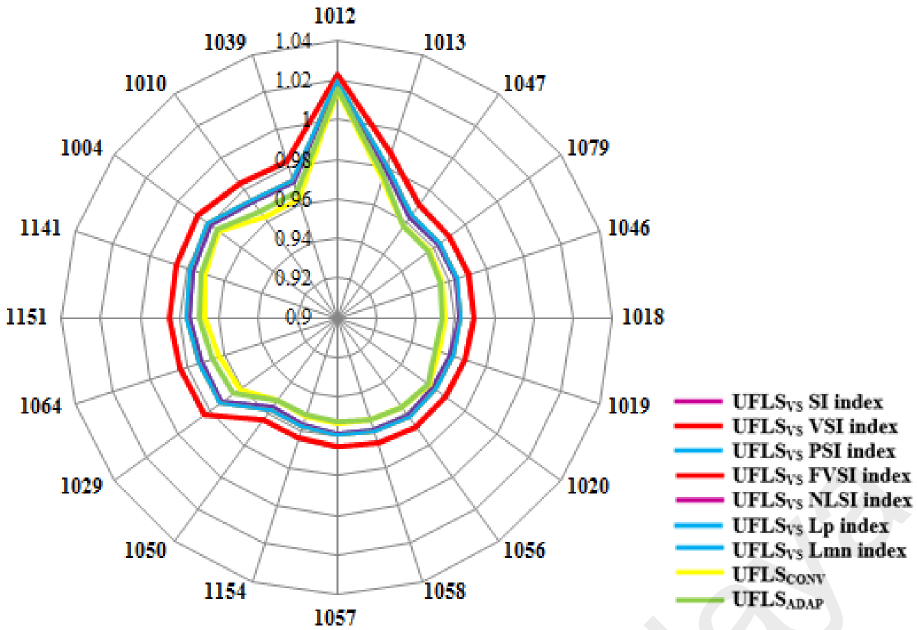


Figure 5.43: Voltage magnitude profile in peak load for Case II

Figure 5.44 shows the comparison of frequency performnace for $UFLS_{CONV}$, $UFLS_{ADAP}$ and proposed $UFLS_{VS}$. For $UFLS_{CONV}$, the frequency decreases to 47.9 Hz before it recovers at 50 Hz. Furthermore, it takes significant amount of time to recover compared to other UFLS schemes. For proposed $UFLS_{VS}$, the VSI, PSI, FVSI, Lp and Lmn index shows fast frequency recovery after load shedding compared to SI and NLSI index.

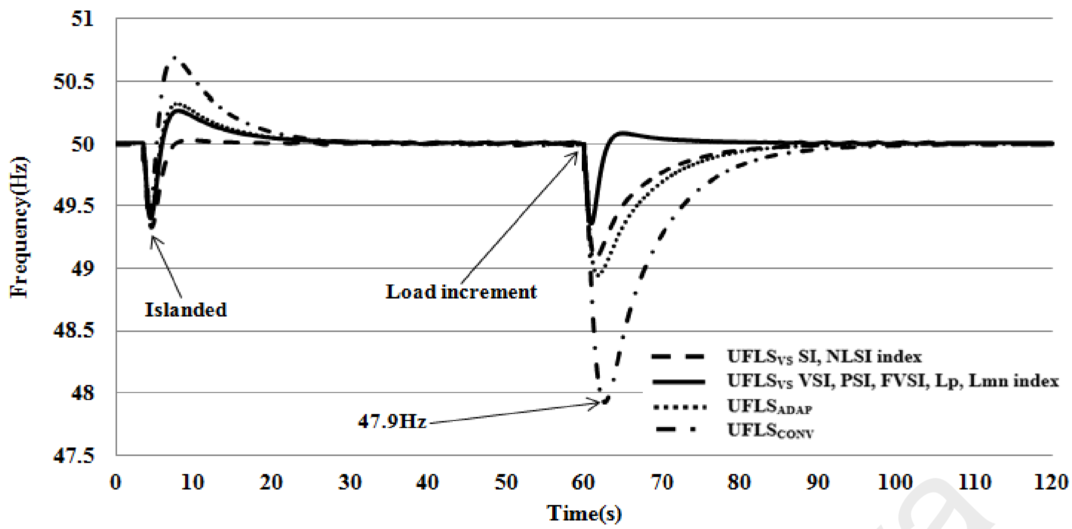


Figure 5.44: Comparison of frequency responses in peak load for Case II

Table 5.16 shows the total load shed for $UFLS_{CONV}$, $UFLS_{ADAP}$ and proposed $UFLS_{VS}$. The amount of load shed by $UFLS_{CONV}$ is 0.6350 MW due to load increment which is higher compared to others load shedding scheme. However, for $UFLS_{VS}$, the amount of load disconnected is less than 0.5 MW (for all stability indices). This amount is less than $UFLS_{CONV}$ and $UFLS_{ADAP}$.

Table 5.16: Analysis for bus number and total shed amount in peak load for Case II

Bus number		1012	1013	1047	1079	1046	1018	1019	1020	1056	1058	1057	1154	1050	1029	1064	1151	1141	1004	1010	1039	Total shed amount (MW)
Load category		Non-vital	Non-vital	Non-vital	Non-vital	Semi-vital	Semi-vital	Vital	Semi-vital	Vital	Non-vital	Non-vital	Semi-vital	Non-vital	Semi-vital	Semi-vital	Vital	Non-vital	Semi-vital	Non-vital	Non-vital	
Techniques																						
UFLS$_{VS}$	**SI**			√					√													0.4882
	VSI								√							√		√				0.4961
	PSI			√					√													0.4882
	FVSI								√							√		√				0.4961
	NLSI			√					√													0.4882
	Lp			√					√													0.4882
	Lmn			√					√													0.4882
UFLS$_{ADAP}$											√	√								√		0.5170
UFLS$_{CONV}$							√	√								√	√					0.6350

5.7 Simulation Results for UFLS Scheme II

The proposed $UFLS_{VS\_LC}$ is tested at peak load condition in which both generators are supplying 3.5872 MW of power. The performance of the proposed $UFLS_{VS\_LC}$ scheme is tested for two different cases:

1) Case I - islanding at 3.5 s
2) Case II - load increment at 60.0 s

5.7.1 Case I - Islanding Operation at 3.5 s

In this section, the performance of proposed $UFLS_{VS\_LC}$ is tested during islanding condition at 3.5 s for peak load scenario.

The analysis for SI ranking is presented in Table 5.17. Table 5.17(a) presents the SI value during grid connected and system islanding. Meanwhile Table 5.17(b) presents the SI value after load shedding. From these two tables, it can be seen that there are changes of bus ranking for load shedding (based on the index value, lowest to highest). For example, before load shedding (Table 5.17(a)), Bus 1047 (SI value = 0.6768) and Bus 1057 (SI value = 0.6814) are at 1st and 2nd ranked respectively. However, when load shed occurs at these two buses, their ranking changes to 10th position (SI value = 0.9917) and 8th position (SI value = 0.9566) respectively as shown in Table 5.17(b). This indicates that their VS value has improved. Should be noted that the analysis for other indices are presented in Table B.22 - B.27 of Appendix B.8.

Table 5.17: Analysis for bus ranked SI value

(a) SI value during grid connected and islanding

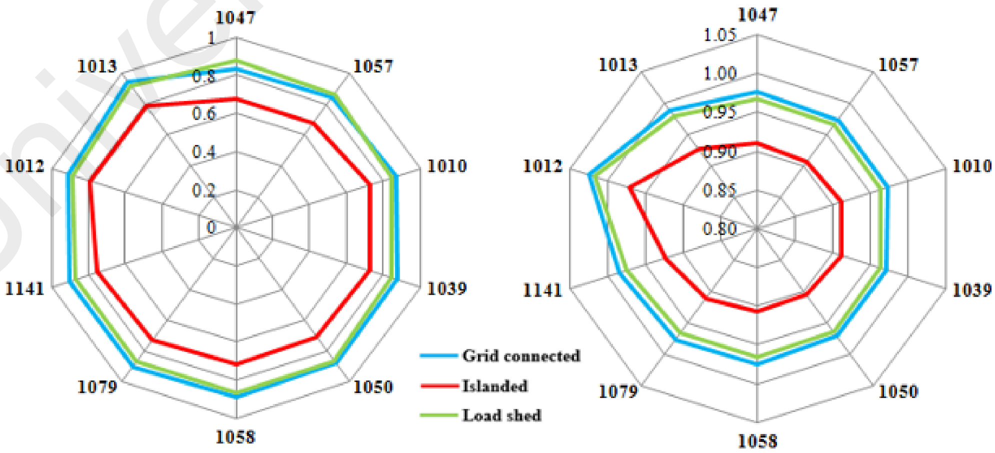
BR_{VS_LC}	$SI_{grid\ connected}$	$SI_{islanded}$
1047	0.8357	0.6768
1057	0.8441	0.6814
1141	0.8728	0.7243
1039	0.8743	0.7253
1050	0.8798	0.7094
1058	0.8857	0.7145
1079	0.9014	0.7305
1010	0.9025	0.7497
1012	0.9108	0.7909
1013	0.9501	0.7891

(b) SI value after load shedding

BR_{VS_LC}	$SI_{load\ shed}$
1010	0.8449
1050	0.8642
1079	0.8683
1058	0.8688
1012	0.8891
1013	0.9205
1039	0.9325
1057	0.9566
1141	0.9912
1047	0.9917

0 = critical 1 = stable

Figure 5.45 shows the overall system performance for SI value. From this figure, it can be seen that when system is islanded, both the VS value and voltage magnitude dropped from higher values (blue line) to lower values (red line). When load shedding is initiated, it can be seen that these values improved significantly as indicated by the green line.



Voltage stability value Voltage magnitude profile

Figure 5.45: Comparison of voltage stability and voltage magnitude for SI

Similar analysis is repeated by using other voltage stability indices; VSI, PSI, FVSI, NLSI, Lp and Lmn. The comparison between VS and voltage magnitude profile for all index are presented in Figure 5.46 to Figure 5.51. However, it should be noted, for these indices the index value that is close to "1" indicates critical condition and close to "0" indicates stable condition.

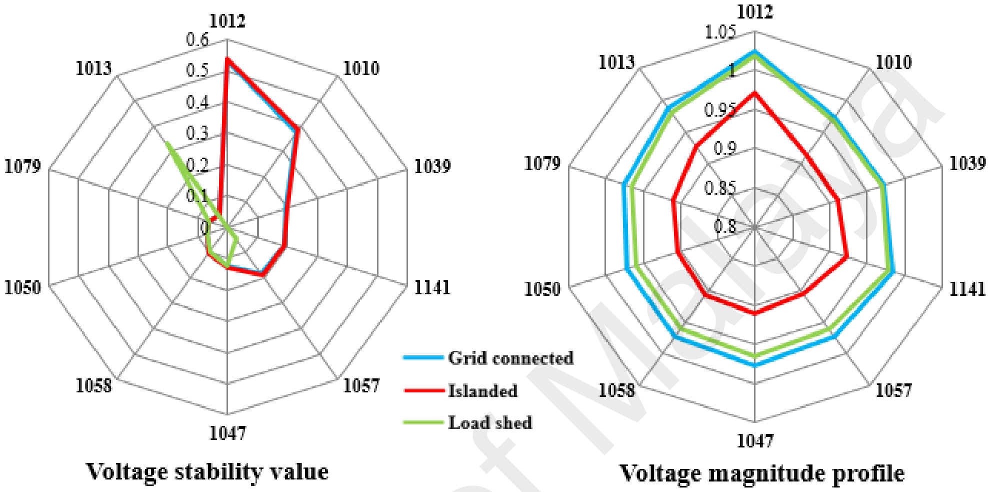


Figure 5.46: Comparison of voltage stability and voltage magnitude for VSI

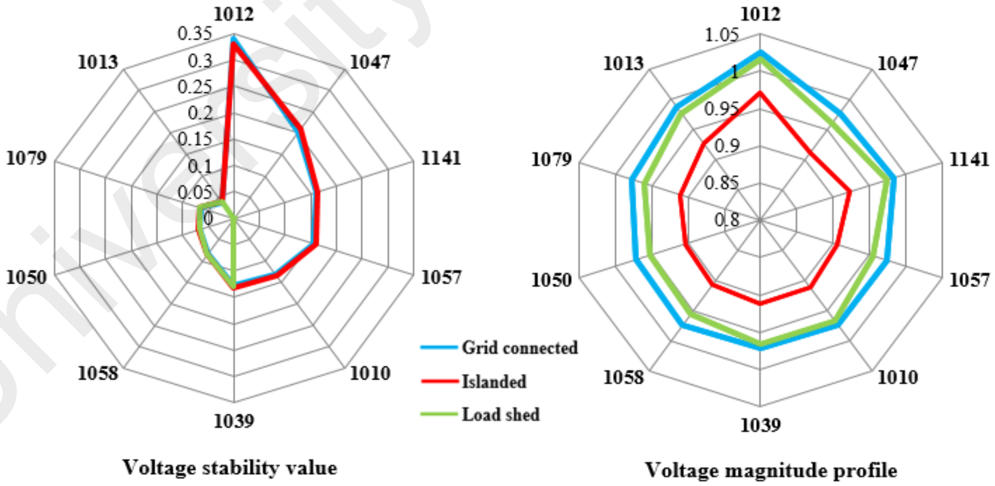


Figure 5.47: Comparison of voltage stability and voltage magnitude for PSI

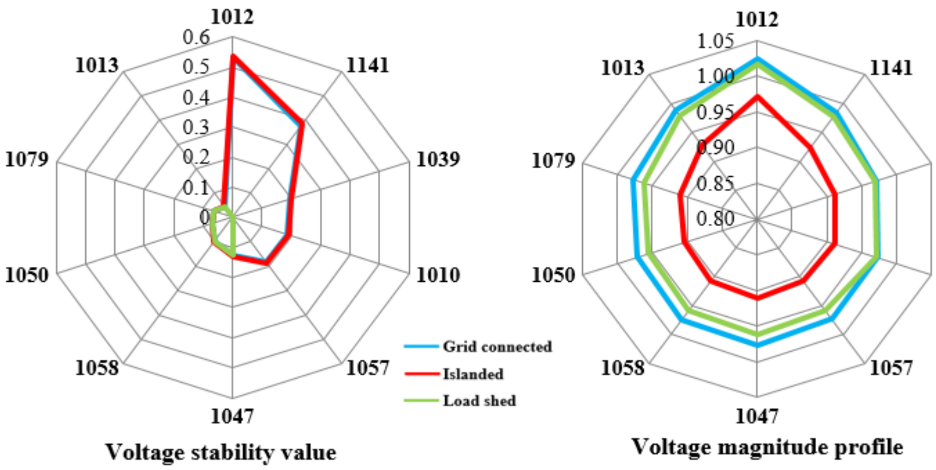


Figure 5.48: Comparison of voltage stability and voltage magnitude for FVSI

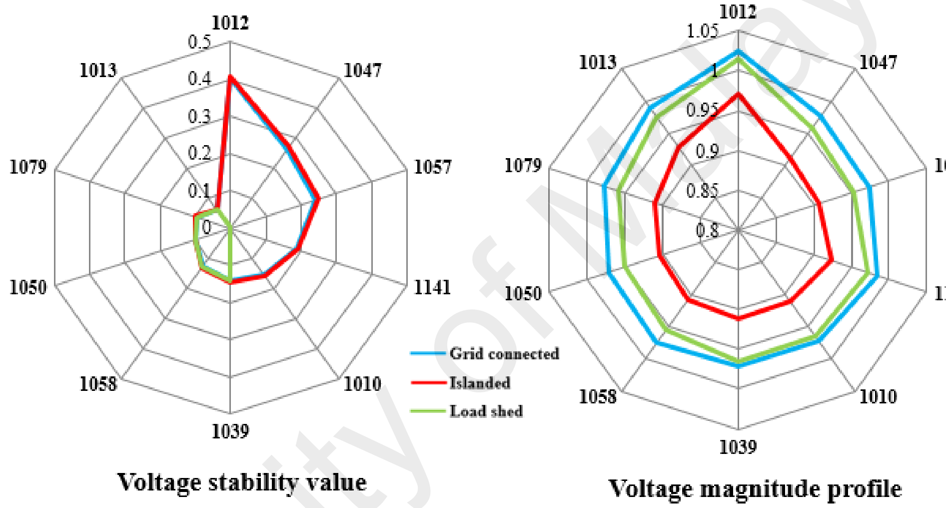


Figure 5.49: Comparison of voltage stability and voltage magnitude for NLSI

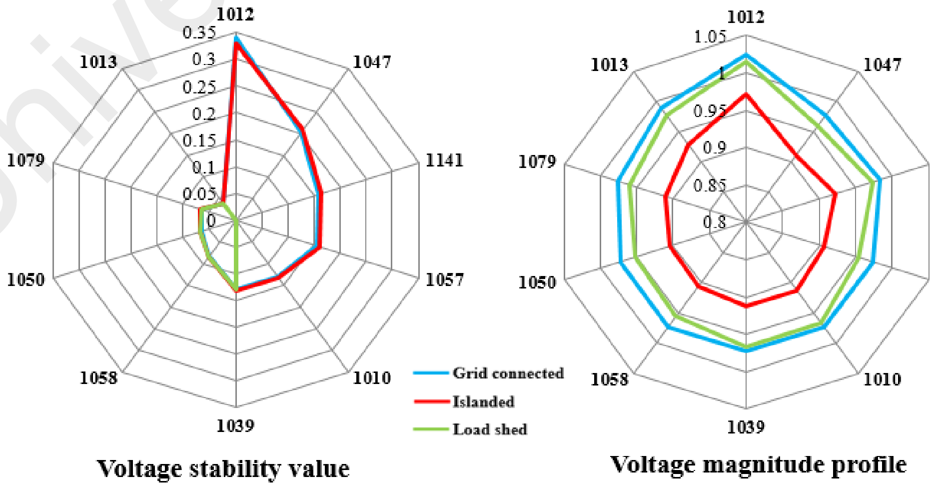


Figure 5.50: Comparison of voltage stability and voltage magnitude for Lp

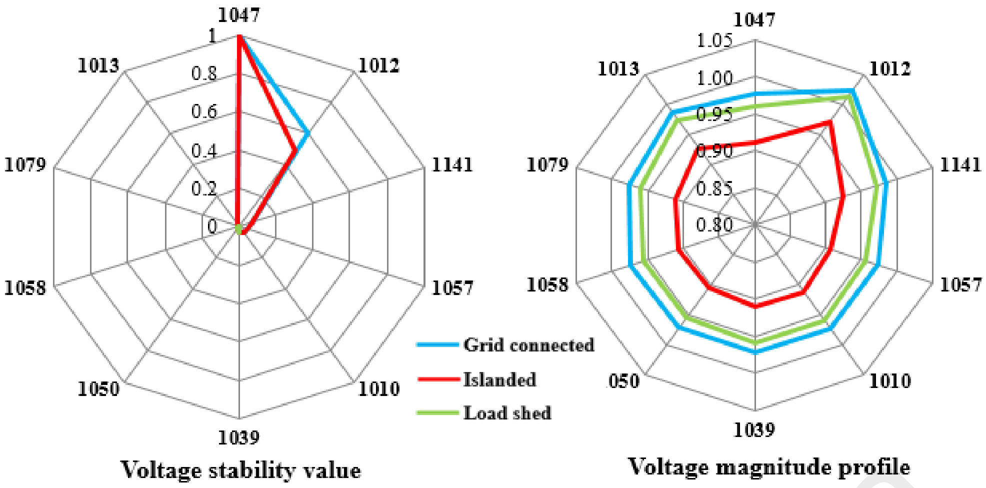


Figure 5.51: Comparison of voltage stability and voltage magnitude for Lmn

The overall performance of voltage magnitude is illustrated in Figure 5.52. It can be observed that proposed $UFLS_{VS\_LC}$ show the highest voltage magnitude improvement compared to $UFLS_{CONV}$ and $UFLS_{ADAP}$. For $UFLS_{VS\_LC}$, VSI and FVSI show the same voltage magnitude. Also, the same pattern is observed for PSI, NLSI, Lp and Lmn index. From the proposed $UFLS_{VS\_LC}$, VSI and FVSI shows significant improvement in voltage magnitude compared to other indices. Furthermore, out of 20 buses, 18 buses show significant improvement in voltage profile which is 90% improvement. The value for voltage profile is presented in Table B.28 of Appendix B.9.

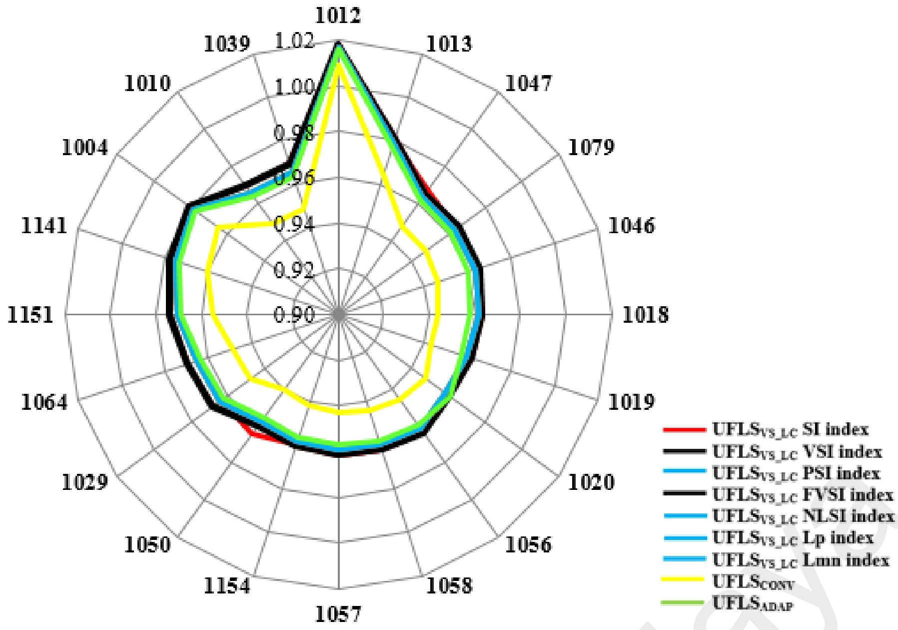


Figure 5.52: Voltage magnitude profile for Case I

Figure 5.53 shows the comparison of frequency performance for $UFLS_{VS\_LC}$, $UFLS_{ADAP}$ and $UFLS_{CONV}$ techniques. The $UFLS_{ADAP}$ and $UFLS_{CONV}$ technique shows higher frequency overshoot of 50.7 Hz and 50.3 Hz respectively as compared to $UFLS_{VS\_LC}$. It can be noted that the proposed $UFLS_{VS\_LC}$ results in less frequency overshoot. From this figure, the PSI, NLSI, Lp, and Lmn index show 50.02 Hz of system frequency overshoot which is less compared to SI, VSI, FVSI (50.25 Hz). The system frequency successfully recovers to its nominal value.

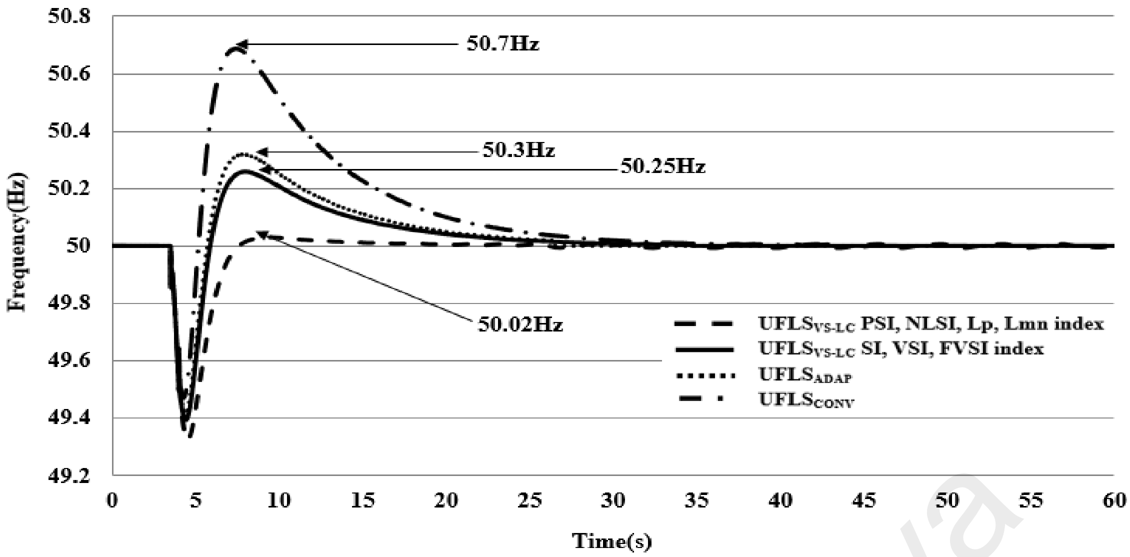


Figure 5.53: Comparison of frequency responses for Case I

Table 5.18 summarizes the amount of load shed for the proposed $UFLS_{VS\_LC}$, $UFLS_{CONV}$ and $UFLS_{ADAP}$ scheme. It can be noticed that the $UFLS_{CONV}$ and $UFLS_{ADAP}$ schemes shed extra loads of 0.7509 MW and 0.6209 MW respectively from the overload scenario. Furthermore, the $UFLS_{CONV}$ and $UFLS_{ADAP}$ scheme has a frequency overshoot of 50.7 Hz and 50.3 Hz respectively. For proposed $UFLS_{VS\_LC}$, sufficient amount of load is shed from the power imbalance value. The total load shed does not exceed the power imbalance value. Also, the load is shed from the non-vital load category. The vital and semi-vital loads are saved and avoided from load being shed.

Table 5.18: Analysis for bus number and total shed amount for Case I

Bus number		1012	1013	1047	1079	1046	1018	1019	1020	1056	1058	1057	1154	1050	1029	1064	1151	1141	1004	1010	1039	Total shed amount (MW)
Load category		Non-vital	Non-vital	Non-vital	Non-vital	Semi-vital	Semi-vital	Vital	Semi-vital	Vital	Non-vital	Non-vital	Semi-vital	Non-vital	Semi-vital	Semi-vital	Vital	Non-vital	Semi-vital	Non-vital	Non-vital	
Techniques																						
UFLS$_{VS}$	**SI**			√								√						√			√	0.4341
	VSI	√										√						√		√	√	0.5826
	PSI	√		√								√				√				√		0.6003
	FVSI	√										√						√		√	√	0.5826
	NLSI	√		√														√		√	√	0.4551
	Lp	√		√								√						√		√		0.5401
	Lmn	√		√								√						√		√		0.5401
UFLS$_{ADAP}$		√	√	√	√									√				√			√	0.6209
UFLS$_{CONV}$		√	√	√	√									√				√		√	√	0.7509

5.7.2 Case II - Load Increment in the System at 60 s

In this section, the performance of proposed $UFLS_{VS\_LC}$ is presented during sudden load increment (0.5MW) in the system.

The analysis for SI index ranking is presented in Table 5.19. Table 5.19(a) presents the SI value during system islanding. Meanwhile Table 5.19(b) presents the SI index for load increment and after load shedding. From these two tables, it can be seen that there are changes of bus ranking due to sudden load increment in the system (based on the index value, lowest to highest). For example, during islanding (Table 5.19(a)), Bus 1079 (SI value = 0.8683) is at 3rd position in the BR_{VS}. However, when sudden load increment occurs in the system, its ranking changes to 1st position in BR_{VS} (SI value = 0.7662) as shown in Table 5.19(b). Also, there are changes of VS value after load shedding (based on the index value, smaller to higher). For example, during load increment (Table 5.19(b)), the SI value for Bus 1079 and Bus 1010 are 0.7662 and 0.7779 respectively. After load shedding, these values increase to 0.8379 and 0.8219 for Bus 1079 and 1010 respectively. This indicates that their VS value has improved. Should be noted that the analysis for other indices are presented in Table B.29 - B.34 of Appendix B.10.

Table 5.19: Analysis for bus ranked SI value

(a) SI value during islanding

BR_{VS_LC}	$SI_{islanded}$
1010	0.8449
1050	0.8462
1079	0.8683
1058	0.8688
1012	0.8891
1013	0.9205
1039	0.9325
1057	0.9566
1141	0.9912
1047	0.9917

(b) SI value for load increment and after load shedding

BR_{VS_LC}	$SI_{load\ increment}$	$SI_{load\ shed}$
1079	0.7662	0.8379
1010	0.7779	0.8219
1050	0.7883	0.8365
1058	0.7926	0.8410
1013	0.8162	0.8617
1012	0.8432	0.8792
1039	0.9311	0.9344
1057	0.9550	0.9567
1141	0.9810	0.9889
1047	0.9911	0.9877

0 = critical 1 = stable

Figure 5.54 shows the overall system performance SI value. From this figure, it can be seen that when load increment occurs, both VS value and voltage magnitude drops from higher values (red line) to lower values (brown line). When load shedding is initiated, it can be seen that these values improved as indicated by the green line.

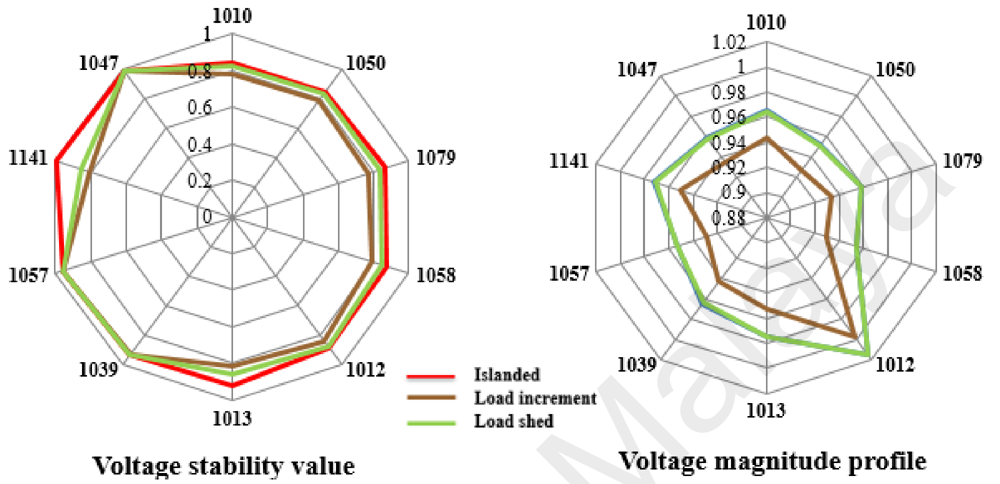


Figure 5.54: Comparison of voltage stability and voltage magnitude for SI

Similar analysis is repeated by using other voltage stability indices; VSI, PSI, FVSI, NLSI, Lp and Lmn. The comparison between VS and voltage magnitude profile for all index are presented in Figure 5.55 to Figure 5.60. However, it should be noted, for these indices the index value that is close to "1" indicates critical condition and close to "0" indicates stable condition.

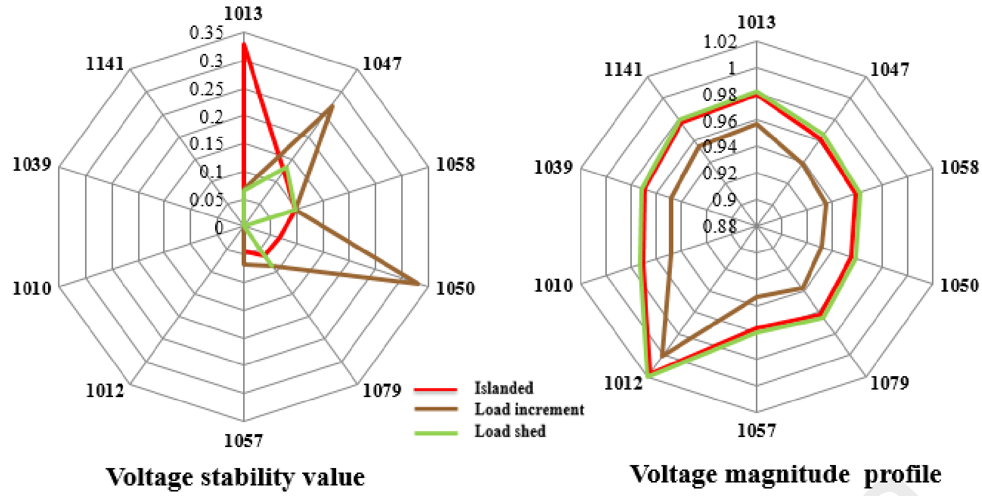


Figure 5.55: Comparison of voltage stability and voltage magnitude for VSI

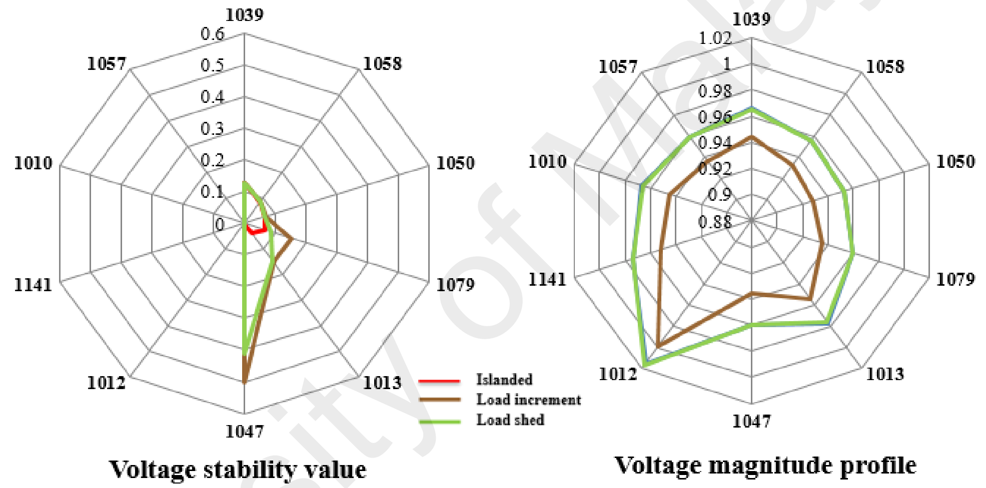


Figure 5.56: Comparison of voltage stability and voltage magnitude for PSI

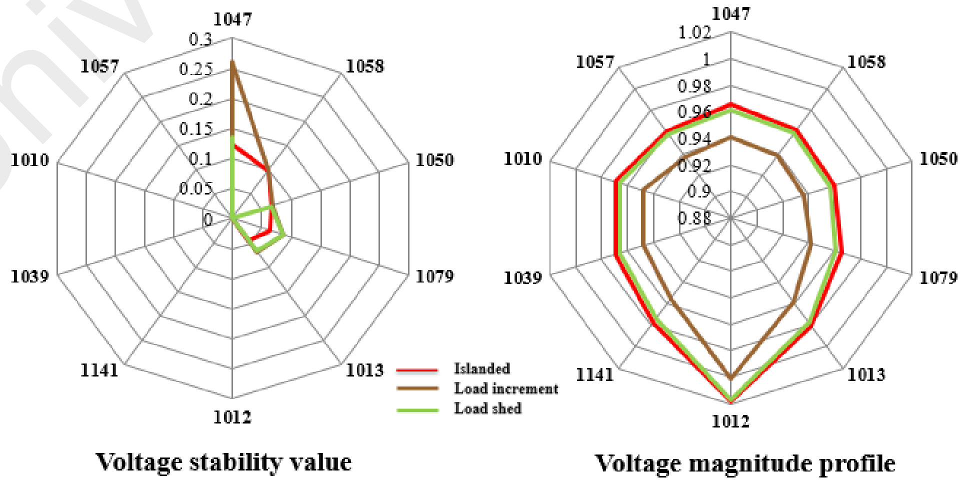
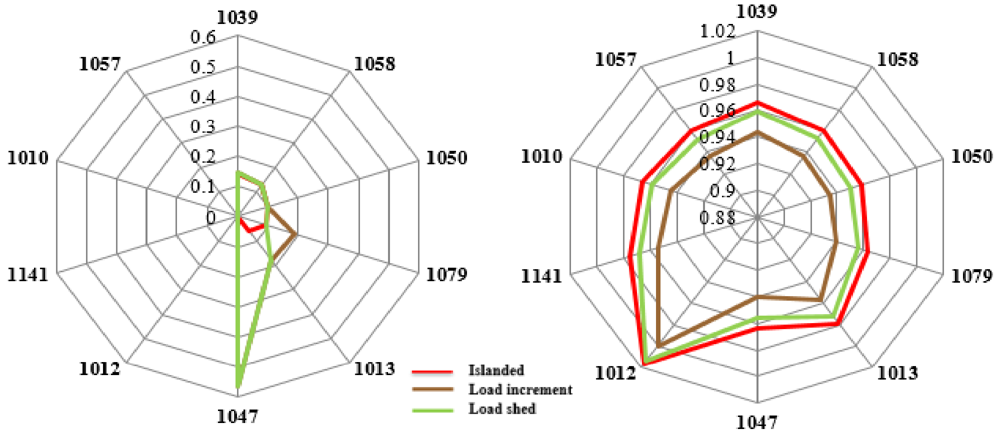


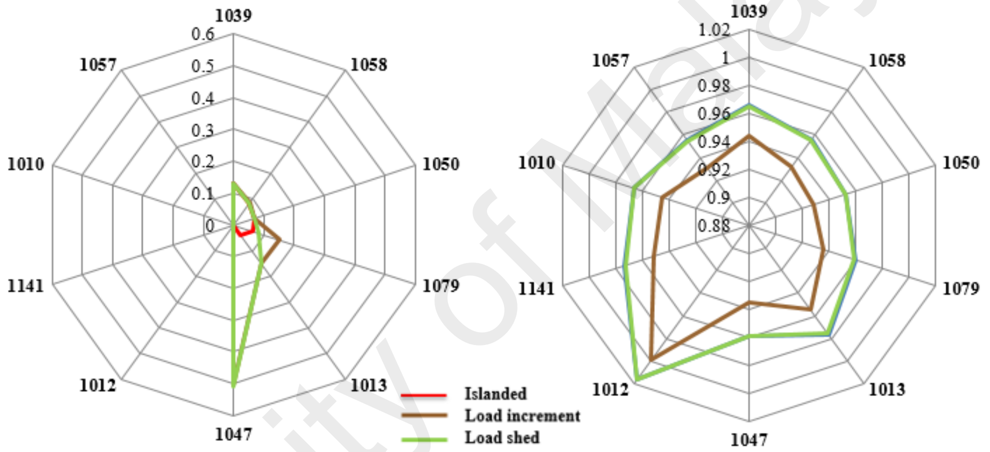
Figure 5.57: Comparison of voltage stability and voltage magnitude for FVSI



Voltage stability value

Voltage magnitude profile

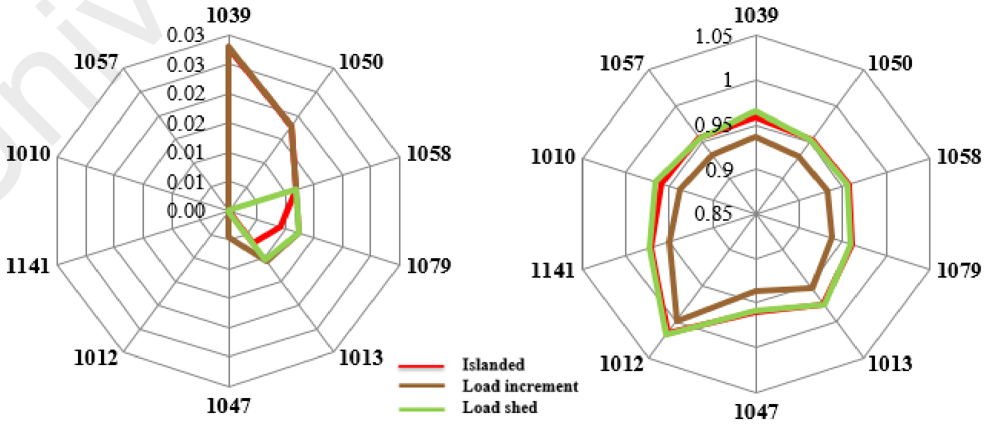
Figure 5.58: Comparison of voltage stability and voltage magnitude for NLSI



Voltage stability value

Voltage magnitude profile

Figure 5.59: Comparison of voltage stability and voltage magnitude for Lp



Voltage stability value

Voltage magnitude profile

Figure 5.60: Comparison of voltage stability and voltage magnitude for Lmn

The overall performance of voltage magnitude is illustrated in Figure 5.61. It can be seen that proposed $UFLS_{VS\_LC}$ for VSI index show the highest voltage magnitude improvement compared to others. Out of 20 buses, 14 buses show much improvement which is 70% improvement. For proposed $UFLS_{VS\_LC}$, PSI, NLSI and Lp index show the same voltage magnitude. The value for voltage magnitude profile is presented in Table B.35 of Appendix B.11.

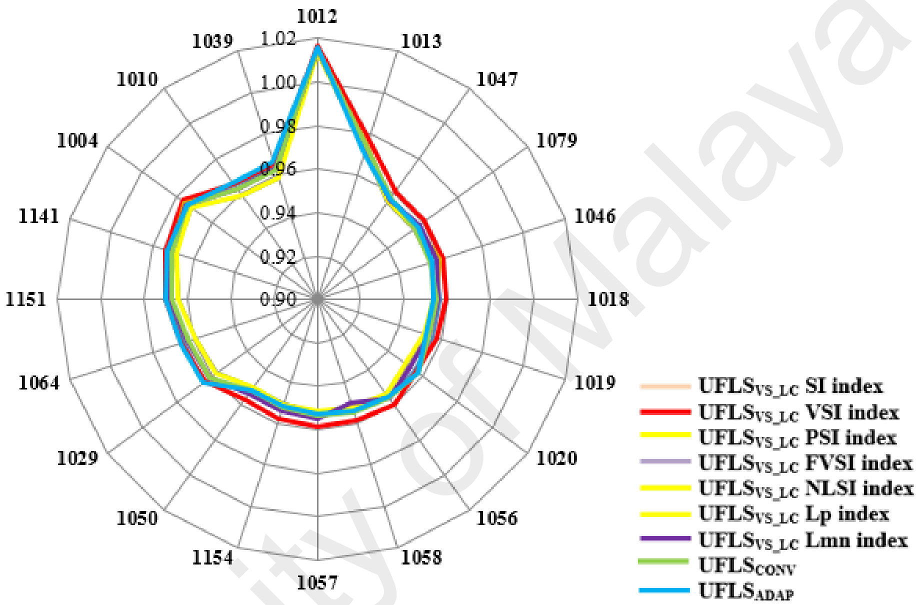


Figure 5.61: Voltage magnitude profile for Case II

Figure 5.62 illustrates the comparison of frequency performance for the proposed $UFLS_{VS\_LC}$, $UFLS_{CONV}$ and $UFLS_{ADAP}$ scheme. In this figure, the $UFLS_{CONV}$ suffers from higher decline of system frequency compared to $UFLS_{ADAP}$ and proposed $UFLS_{VS\_LC}$. For $UFLS_{CONV}$, the frequency has undershot of 47.9 Hz. However, for the proposed $UFLS_{VS\_LC}$, the SI, VSI and FVSI shows fast recovery of system frequency compared to other indices.

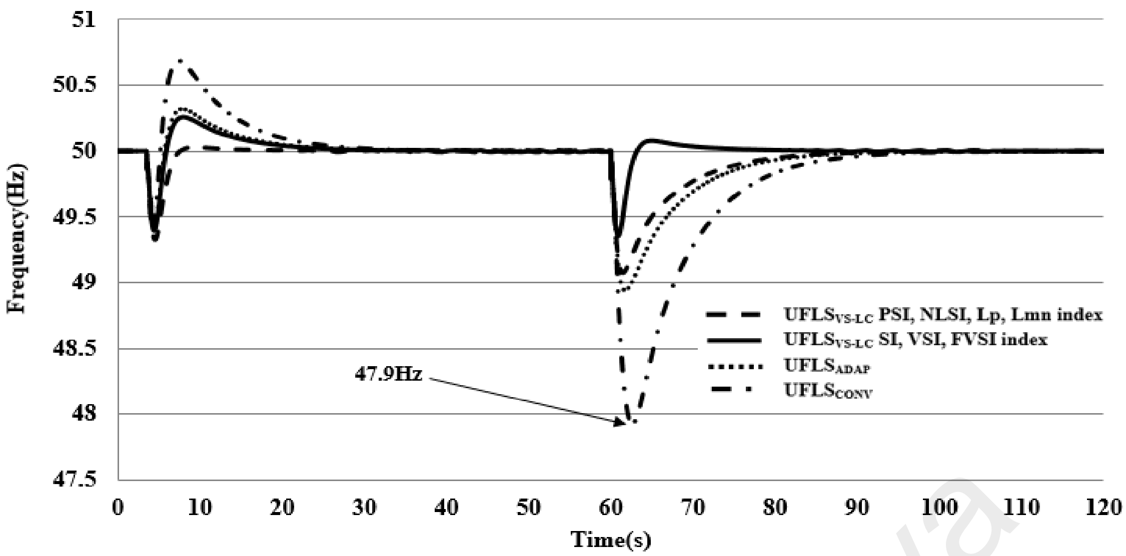


Figure 5.62: Comparison of frequency responses for Case II

Table 5.20 shows the total load shed for $UFLS_{CONV}$, $UFLS_{ADAP}$ and $UFLS_{VS\_LC}$. The $UFLS_{CONV}$ shows that 0.6350 MW of load is shed due to load increment compared to other load shedding schemes. The load shed by $UFLS_{CONV}$ and $UFLS_{ADAP}$ is 0.6350 MW and 0.5170 MW respectively.

Table 5.20: Analysis for bus number and total shed amount for Case II

Bus number		1012	1013	1047	1079	1046	1018	1019	1020	1056	1058	1057	1154	1050	1029	1064	1151	1141	1004	1010	1039	Total shed amount (MW)
Load category		Non-vital	Non-vital	Non-vital	Non-vital	Semi-vital	Semi-vital	Vital	Semi-vital	Vital	Non-vital	Non-vital	Semi-vital	Non-vital	Semi-vital	Semi-vital	Vital	Non-vital	Semi-vital	Non-vital	Non-vital	
Techniques																						
UFLS$_{VS}$	**SI**				√																	0.2679
	VSI			√										√								0.3210
	PSI				√																	0.2679
	FVSI				√																	0.2679
	NLSI				√																	0.2679
	Lp				√																	0.2679
	Lmn													√							√	0.2135
UFLS$_{ADAP}$											√	√								√		0.5170
UFLS$_{CONV}$							√	√								√	√					0.6350

5.8 Discussions

The proposed $UFLS_{VS}$ is validated on 25 bus tests system during light and peak load condition. From the simulation results, it can be observed that proposed $UFLS_{VS}$ leads to enhancement of voltage performance in the islanding and load increment scenario. Furthermore, the proposed scheme has better voltage profile due to VS index.

In the proposed scheme, the most suitable VS index is investigated which is applicable for distribution test system. The simulations are carried out in order to test the performance of voltage profile with $UFLS_{VS}$ and $UFLS_{VS\_LC}$. For proposed $UFLS_{VS}$ in peak load scenario, the VSI, PSI, FVSI, Lp and Lmn shows higher voltage magnitude for Case I peak load. Meanwhile, for Case II, the VSI and FVSI shows higher voltage magnitude compared to other indices. For $UFLS_{VS\_LC,}$ the VSI and PSI index shows higher voltage magnitude for Case I while the FVSI and VSI shows higher voltage magnitude for Case II. From this, the VSI shows better voltage performance in most cases for $UFLS_{VS}$ and $UFLS_{VS\_LC.}$

Furthermore, it has been observed that from the simulation results, the proposed scheme is able to restore the system frequency with less overshoot after being subjected to disturbances However, $UFLS_{CONV}$ and $UFLS_{ADAP}$ schemes have higher overshoot in their frequency response for islanding and load increment cases. This proves that the proposed algorithms have achieved optimal load shedding.

Moreover, this research has proposed two UFLS schemes namely $UFLS_{VS}$ and $UFLS_{VS\_LC}$. From the simulation results, it has been observed that although $UFLS_{VS}$ can improve the voltage and frequency performance, the proposed scheme involves vital load in the system. Hence, $UFLS_{VS\_LC}$ is proposed in order to save the vital loads and semi vital loads in the system.

5.9 Chapter Summary

This chapter has presented the validation of the proposed of $UFLS_{VS}$ and $UFLS_{VS\_LC}$ under various test scenarios. The effectiveness of the proposed $UFLS_{VS}$ algorithm have been investigated on islanding event and load increment case in the system. Response of the proposed $UFLS_{VS}$ is compared with both $UFLS_{CONV}$ and $UFLS_{ADAP}$ scheme. The simulation results have shown that the proposed scheme can enhance the voltage and frequency profile of the system compared to the $UFLS_{CONV}$ and $UFLS_{ADAP}$ scheme. Furthermore, the proposed $UFLS_{VS}$ has shed optimal amount of load compared to the $UFLS_{CONV}$ and $UFLS_{ADAP}$ load shedding scheme. In terms of VS index, the VSI shows higher voltage magnitude improvement compared other indices in both cases (Case I and Case II) for peak load condition.

Apart from this, this chapter has presented the simulation results for $UFLS_{VS\_LC}$ in order to address the limitation of $UFLS_{VS}$. The effectiveness of the proposed $UFLS_{VS\_LC}$ is validated from the simulation during islanded and sudden load increment in the system. The simulation results have shown that the proposed scheme can enhance the voltage and frequency performance compared to the $UFLS_{CONV}$ and $UFLS_{ADAP}$ scheme. The proposed $UFLS_{VS\_LC}$ has shed optimal amount of load compared the $UFLS_{CONV}$ and $UFLS_{ADAP}$ scheme. The major advantage from $UFLS_{VS\_LC}$ compared to $UFLS_{VS}$ is the consideration of load category in the proposed algorithms. Through this, the vital and semi-vital load is protected from disconnection in the proposed algorithms. In terms of VS index, the VSI shows higher voltage magnitude improvement compared to other indices in both cases (Case I and Case II) for peak load condition.

CHAPTER 6: VALIDATION OF THE PROPOSED ANALYTICAL HIERARCHY PROCESS METHOD FOR OPTIMAL LOAD SELECTIVITY

6.1 Introduction

The previous chapter details the analyses of the proposed Under Frequency Load Shedding Scheme based on Voltage Stability ($UFLS_{VS}$) and the proposed Under Frequency Load Shedding Scheme based on Voltage Stability (VS) and Load Category ($UFLS_{VS\_LC}$). This chapter will describe further the analyses of the proposed load shedding scheme for optimal load selectivity. Two sets of load combination are determined (COM1 and COM2), and the weight value for each alternative is analysed using the Analytical Hierarchy Process (AHP) decision making technique. The proposed Under Frequency Load Shedding According AHP ($UFLS_{AHP}$) is then simulated during the peak load scenario. In order to validate the effectiveness of proposed $UFLS_{AHP}$, the simulation results are compared with Under Frequency Load Shedding According Voltage Stability and Load Category ($UFLS_{VS\_LC}$), Adaptive Under Frequency Load Shedding ($UFLS_{ADAP}$), and Conventional Under Frequency Load Shedding ($UFLS_{CONV}$).

6.2 Analysis for Proposed Optimal Combination of Least Error Module

The Optimal Combination of Least Error Module (OCLEM) is introduced to develop several possible load combinations from the $UFLS_{VS\_LC}$. This is to avoid the vital and semi-vital loads during the load shedding process. The load combinations can be determined by using the equation (4.1), which means that there are 1024 sets of possible load combinations from the proposed OCLEM as presented in Table C.1 until Table C.13 of Appendix C. The error value (difference between total power and power imbalance) from each combination can also be calculated. From this, two sets of loads, with Minimum Error from Load Combination (MELC), can be accessed and referred as COM1 and COM2. It should be pointed out that the load combinations value is a bus number as presented in Table 6.1.

Table 6.1: Bus number value for load combinations

Value of load combinations	Bus number
1	1012
2	1013
3	1047
4	1079
5	1058
6	1057
7	1050
8	1141
9	1010
10	1039

From the OCLEM proposed algorithms, two sets of MELC, corresponding to 0.0002 and 0.0013, can be determined from Tables C.10 and C.5 (in Appendix C), respectively. Table 6.2 summarizes two sets of MELC from the OCLEM proposed algorithms. These sets of MELC are transmitted to the Analytical Hierarchy Process Module (AHPM) for decision-making analysis.

Table 6.2: Set of minimum error load combination

Set of loads combination	Variable of load combinations	Bus number	Error
COM1	3,5,6,10	1047, 1058, 1057, 1039	0.0002
COM2	1, 3, 5, 8, 9, 10	1012, 1047, 1058, 1141, 1010, 1039	0.0013

6.3 Analysis for Proposed Analytical Hierarchy Process Module

From the proposed of Analytical Hierarchy Process Module (AHPM), the normalized weight for criteria and alternative can be determined and analysed for both COM1 and COM2. According to Table 6.2, for COM1, there are four buses involved; Bus 1047, 1058, 1057 and 1039, with a minimum error of 0.0002. Meanwhile, there are six buses involved; Bus 1012, 1047, 1058, 1141, 1010 and 1039, with a minimum error 0.0013 for COM2. These buses are represented as an alternative. For the AHP analysis, each alternative is represented as a weight value. This weight value is determined based on the balance comparison for the stability criteria and load criteria by using the AHP decision making technique, as illustrated in Figure 6.1.

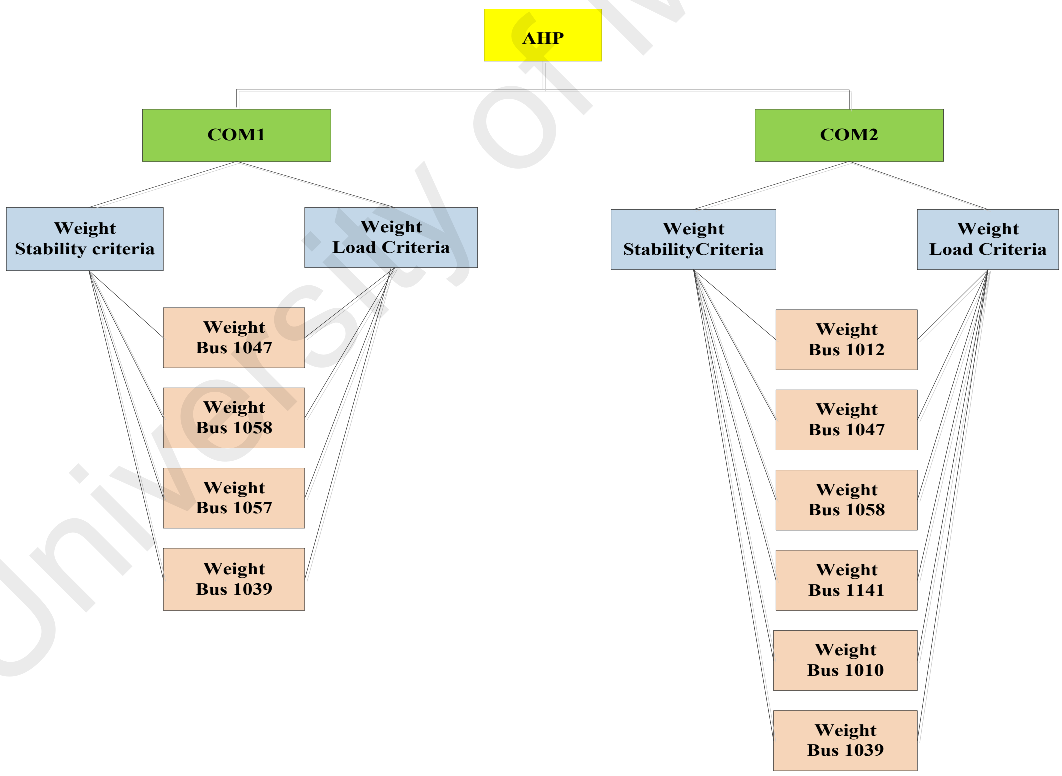


Figure 6.1: Decision making using analytical hierarchy process

According to Figure 6.1, the weight for both criteria (stability and load) is analysed for COM1 and COM2 using the AHP decision making technique. The same technique is used to determine the weight of alternatives for COM1 and COM2. The Bus Ranked according AHP (BR_{AHP}) is developed from the weight value of the alternatives.

The BR_{AHP} is ranked in a descending order, where the highest weight value is ranked in the top of BR_{AHP}. In the case where the same buses are presented for COM1 and COM2, only the highest of weight value is considered at particular combinations for BR_{AHP}. It should be noticed that the normalized weight is considered in the AHP analysis. Then, the BR_{AHP} is transmitted to the Load Shedding Controller Criteria Module (LSCCM) for load shedding. This module is activated in the event of system disturbances.

6.3.1 Analysis for Analytical Hierarchy Process SI Value

In this section, the weight for each criteria and alternatives is analysed as shown in Figure 6.2. It should be noted that this analysis is for Stability Index (SI) value. The weight for criteria and alternative can be determined by using equation (4.3) - (4.11) and equation (4.12) - (4.17) respectively (mentioned in Chapter 4).

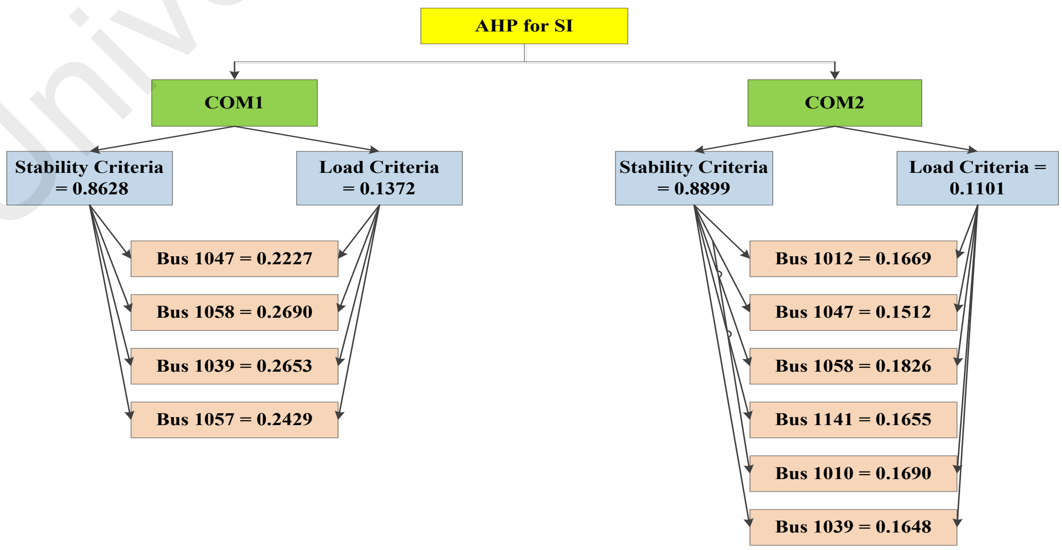


Figure 6.2: Weight for analytical hierarchy process decision making SI index

The initial step for AHP analysis is to determine the weight for each criterion for both COM1 and COM2. For COM1, the weight stability and load criteria are 0.8628 and 0.1372 respectively. Meanwhile for COM2, the weight stability and load criteria are 0.8899 and 0.1101 respectively. The sum of weight for both criteria (stability and load) needs to be "1". According to this figure, it can be seen that the weight for the stability criteria is more dominant (shows higher weight value) compared to the load criterion for both combinations (COM1 and COM2).

There is also a situation where some alternative (Bus 1047, 1058 and 1039) are similar for both combinations (COM1 and COM2), as shown in Figure 6.3. In this case, the AHPM only considered the highest weight and eliminated the lowest weight value as shown in Figure 6.3. For example, for bus 1047, the AHPM select the weight 0.2227 in COM1 instead of COM2 (weight value = 0.1512).

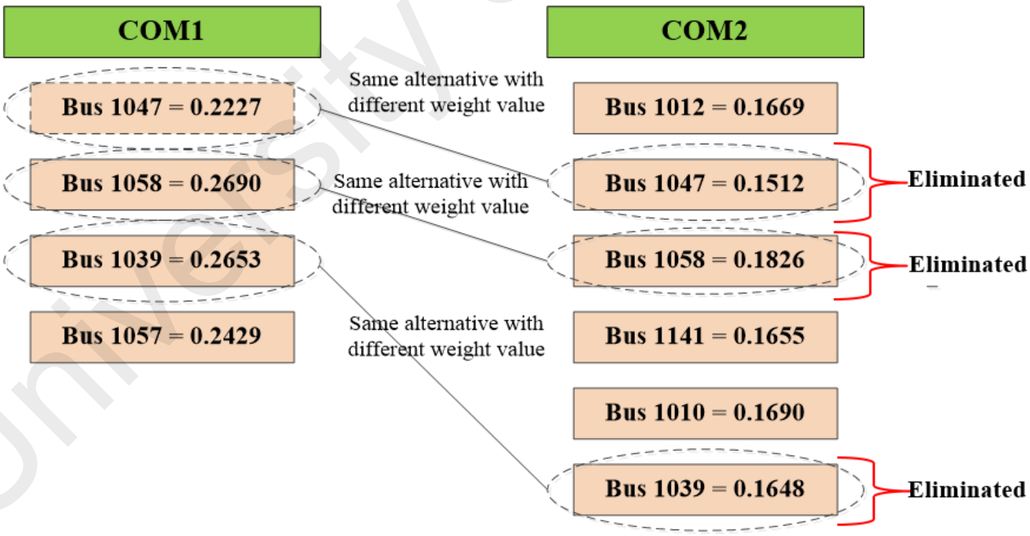


Figure 6.3: Proposed load selection technique based analytical hierarchy process

After Bus 1047, 1058, and 1039 for COM2 are eliminated, the proposed AHPM will search the highest of weight value from the alternative (remaining 7 buses out of 10), and ranked the weight in a descending order, as shown in Figure 6.4. Then, the BR_{AHP} is developed and transmitted to the LSCCM. During system disturbances, the LSCCM is initiated and load is shed according to the BR_{AHP}.

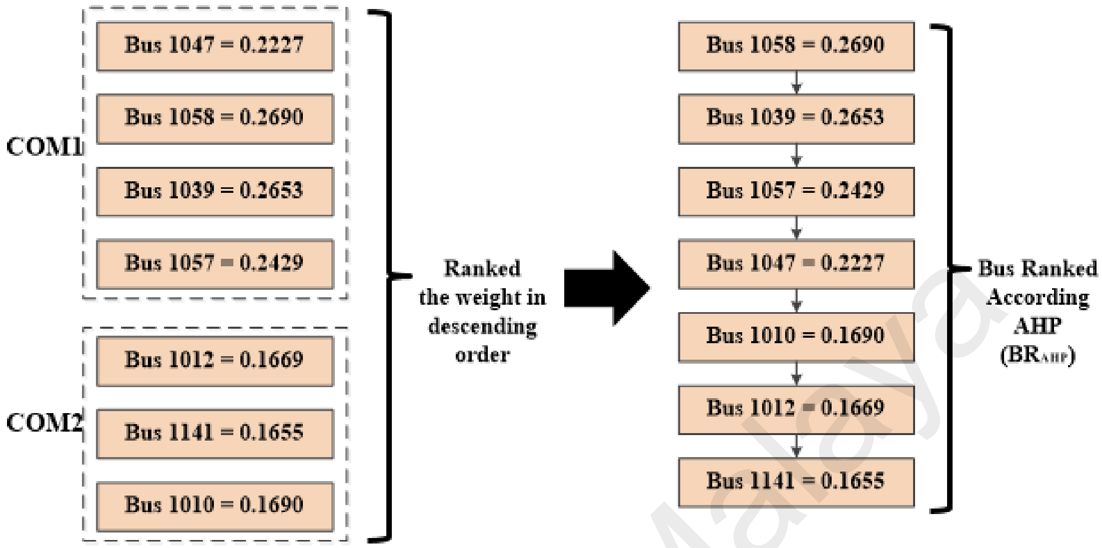


Figure 6.4: Proposed bus ranked according analytical hierarchy process

Table 6.3 shows the BR_{AHP} developed for the SI value. According to this table, it can be observed that Bus 1058 is the highest weight value (0.2690) compared to the other buses using the AHP decision making technique.

Table 6.3: Bus ranked according AHP for SI value

BR_{AHP} for SI value	Bus number	AHP weight
1	1058	0.2690
2	1039	0.2653
3	1057	0.2429
4	1047	0.2227
5	1010	0.1690
6	1012	0.1669
7	1141	0.1655

The same procedure is repeated for the other indices to determine the weight criteria and alternative, as presented in Appendix D.

6.4 Validation of the Proposed Load Shedding Scheme According Analytical Hierarchy Process

In this section, the simulation results for the proposed of Under Frequency Load Shedding According Analytical Hierarchy Process ($UFLS_{AHP}$) are presented. This scheme comprises of the load selectivity according to the least error of load combination. The Voltage Stability (VS) criteria and load criteria are analysed based on the AHP decision making. The peak load scenario is simulated with a total load demand of 3.5872 MW. The test system is modelled using PSCAD/EMTDC, as shown in Figure B.1 in Appendix B.1.

In order to test the effectiveness of the proposed scheme, it is simulated for different cases, and explained in Section 5.3:

1) Case I - intentional islanding
2) Case II - load increment

From the simulation results for the proposed of $UFLS_{VS}$ and $UFLS_{VS\_LC,}$ it can be summarized that the Voltage Stability Index (VSI) is the best index that produces excellent overall voltage magnitude in most cases. The VSI is then selected for implementation in the proposed $UFLS_{AHP}$ for optimal load selectivity. Figure 6.5 shows the weight for all criteria and alternatives (bus number) according to the AHP decision-making techniques. It can be seen that the stability criteria are more dominant for both combination, which is 0.5252 and 0.6982 for COM1 and COM2 respectively.

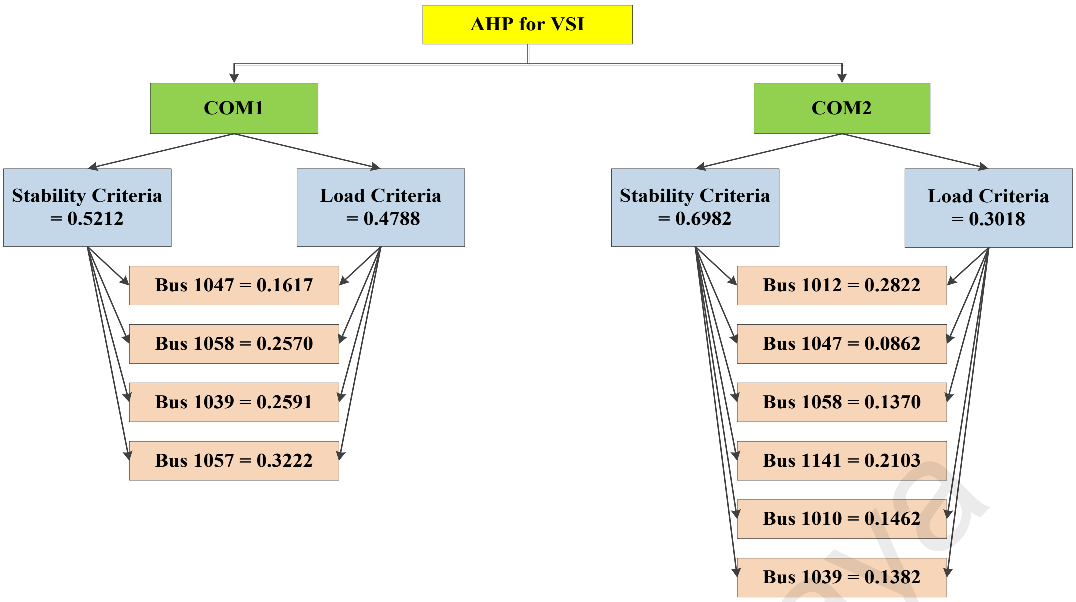


Figure 6.5: VSI weight for analytical hierarchy process

Meanwhile, the weight for all alternatives (bus number) is analysed and ranked in the BR_{AHP} as tabulated in Table 6.4. According to this table, it can be observed that Bus 1057 is the highest weight value (0.3222) compared to the other buses using the AHP decision making technique for VSI. Then, the proposed load shedding scheme is performed according the BR_{AHP} during sudden disturbances in the system.

Table 6.4: Bus ranked according AHP for VSI value

BR_{AHP} for VSI value	Bus number	AHP weight
1	1057	0.3222
2	1012	0.2822
3	1039	0.2591
4	1058	0.2570
5	1141	0.2103
6	1047	0.1617
7	1010	0.1462

In the last section, the proposed of $UFLS_{AHP}$ is compared with $UFLS_{CONV}$, $UFLS_{ADAP}$ and $UFLS_{VS\_LC}$ during system islanded and sudden load increment in the system. The voltage magnitude profile and system frequency response are analysed from the simulation results.

6.5 Simulation Results for Proposed Under Frequency Load Shedding According Analytical Hierarchy Process

In this section, the proposed of $UFLS_{AHP}$ is simulated using two different cases:

1) Case I - islanding at 3.5 s
2) Case II - load increment at 60.0 s

6.5.1 Case I - Islanding Operation at 3.5s

The analysis for bus ranking according AHP weight value and VSI value is presented in Table 6.5. Table 6.5(a) presents the VSI value during grid connected and system islanding. Meanwhile, Table 6.5(b) presents the VSI value after load shedding. From these two tables, it can be seen that there are changes of VSI value after load shedding (based on the index value, higher to lower). For example, before load shedding (Table 6.5(a)), the VSI value is 0.1890 for Bus 1057. However, after load shedding the VSI value is 0.0001 as shown in Table 6.5(b). This indicates that their VSI value has improved.

Table 6.5: Analysis for bus ranked according analytical hierarchy process

(a) VSI value for grid connected and system islanding

BR_{AHP}	$VSI_{grid\ connected}$	$VSI_{islanded}$
1057	0.1827	0.1890
1012	0.5194	0.5689
1039	0.1956	0.1996
1058	0.0978	0.2010
1141	0.3744	0.3940
1047	0.1235	0.1293
1010	0.1869	0.1908

(b) VSI value after load shedding

BR_{AHP}	$VSI_{load\ shed}$
1047	0.1243
1010	0.1867
1058	0.1997
1141	0.3753
1012	0.0001
1039	0.0001
1057	0.0001

1 = critical 0 = stable

In order to see the overall system performance during grid connected, islanding and after load shedding, the VSI value at all buses are plotted in a form of spider-web chart, shown in Figure 6.6. From this figure, it can be noticed that when system is islanded, the VSI value is increased from lower values (blue line) to higher values (red line). When load shedding is initiated, it can be seen that these values is improved as indicated by the green line.

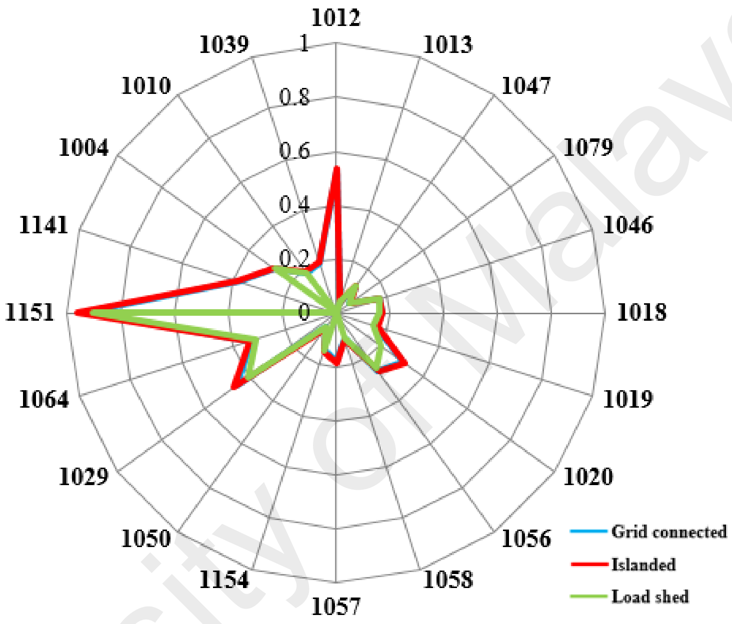


Figure 6.6: **Voltage stability value for VSI index for Case I**

6.5.2 Case II – Load increment at 60.0 s

Following system islanding, the LSCCM is initiated, and 0.4414 MW of load is disconnecting from the system. Taking this occurrence into account, the total generation was 3.1458 MW when system is islanded. During sudden load increment, certain buses increased its active power load value by 0.5 MW of load demand in the system, making the total load value is 3.6458 MW. Based on this condition, the overload scenario is detected when the total load demand, 3.6458 MW, exceeds the DG capacity, 3.6 MW.

The analysis for bus ranking according AHP weight value for VSI is presented in Table 6.6. Table 6.6(a) presents the VSI value when system is islanded. Meanwhile, Table 6.6(b) presents the VSI value for load increment and after load shedding. From these two tables, it can be summarized that there are changes of VSI value after load shedding (based on the index value, higher to lower). For example, before load shedding (Table 6.6(a)), the VSI value is 0.1997 for Bus 1058. However, after load shedding the VSI value is 0.0001 as shown in Table 6.6(b). This indicates that their VSI value has improved.

Table 6.6: Analysis for bus ranked according analytical hierarchy process

(a) VSI value during islanding

BR_{AHP}	$VSI_{islanded}$
1047	0.1243
1010	0.1867
1058	0.1997
1141	0.3753
1012	0.0001
1039	0.0001
1057	0.0001

(b) VSI value for load increment and after load shedding

BR_{AHP}	$VSI_{load\ increment}$	$VSI_{load\ shed}$
1047	0.1302	0.1266
1010	0.1901	0.1880
1058	0.2007	0.0001
1141	0.3801	0.0001
1012	0.0001	0.0001
1039	0.0001	0.0001
1057	0.0001	0.0001

1 = critical 0 = stable

Figure 6.7 shows the overall system performance of VSI value during system islanding, load increment and after load shedding. From this figure, it can be observed that when sudden load increment, the VSI value is increased from lower values (red line) to higher values (brown line). When load shedding is initiated, it can be seen that these values is improved as indicated by the green line.

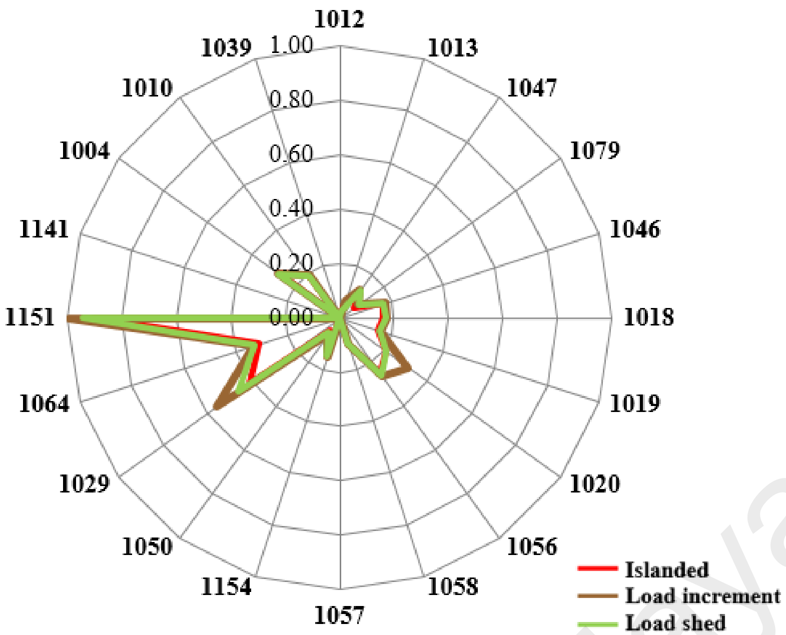


Figure 6.7: Comparison of voltage stability and voltage magnitude for VSI index

6.6 Comparison of proposed $UFLS_{AHP}$ with $UFLS_{VS\_LC}$, $UFLS_{ADAP}$ and $UFLS_{CONV}$

This section details the comparison between the voltage magnitude profile and frequency performance for the proposed $UFLS_{AHP}$, $UFLS_{VS\_LC}$, $UFLS_{ADAP}$, and $UFLS_{CONV}$. Two cases are accounted for in this section:

1) Case I - islanding at 3.5 s
2) Case II - load increment at 60.0 s

6.6.1 Case I - Islanding Operation at 3.5s

The performance of the proposed $UFLS_{AHP}$ is analysed when the system is islanded. In order to test the effectiveness of the proposed scheme, the voltage magnitude profile for $UFLS_{AHP}$ is compared with $UFLS_{VS\_LC}$ (for VSI), $UFLS_{ADAP}$, and $UFLS_{CONV}$, as shown in Figure 6.8. It can be observed that $UFLS_{AHP}$ shows higher voltage magnitude profile compared to the others. Out of the 20 buses, 18 buses show higher voltage magnitude, which is contributed 90% of improvement. Through this, the proposed

UFLS$_{AHP}$ shows better performance for the overall system compared to the other load shedding techniques.

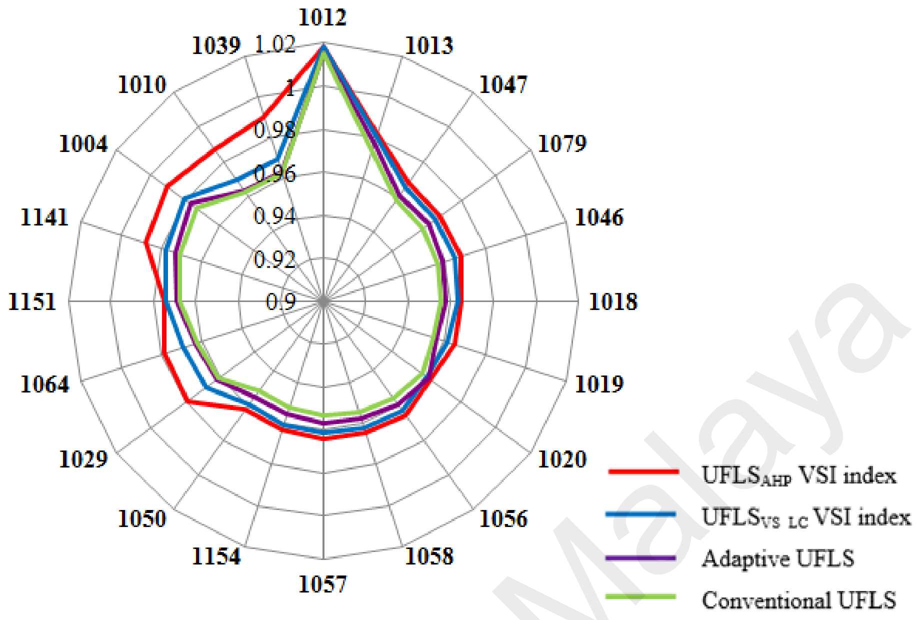


Figure 6.8: Comparison of voltage magnitude profile for Case I

Figure 6.9 shows the frequency response for the different load shedding techniques. It can be seen that proposed of UFLS$_{AHP}$ shows no overshoots in frequency response compared to the UFLS$_{VS_LC}$, UFLS$_{AHP}$, and UFLS$_{CONV}$. For the proposed UFLS$_{VS_LC}$, the frequency response contains overshoot and increased to 50.2 Hz. However, this value is not high as UFLS$_{AHP}$ and UFLS$_{CONV}$ which is at 50.3 Hz and 50.7 Hz, respectively.

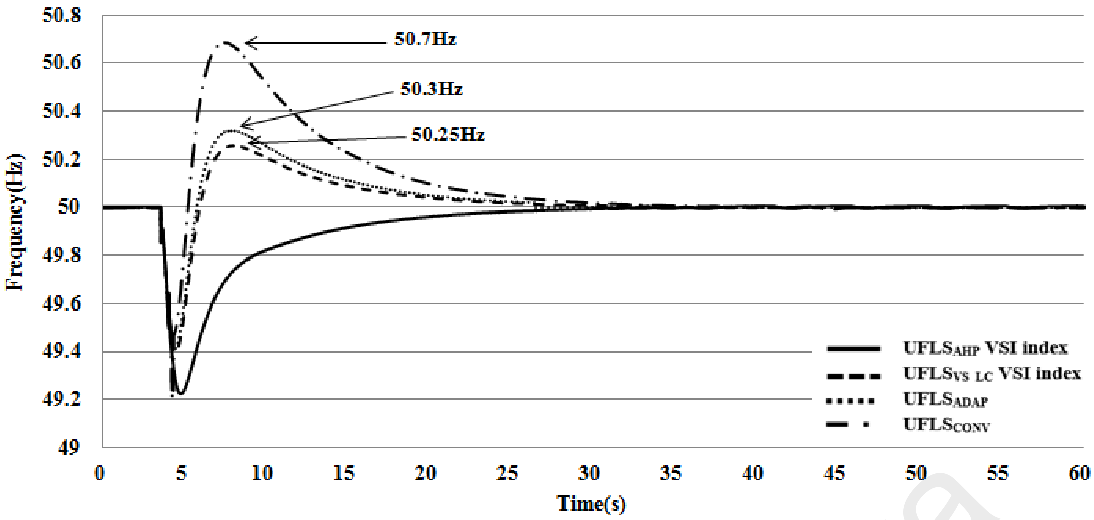


Figure 6.9: Comparison of frequency responses for Case I

Table 6.7 details the analysis for the amount of shed load. Following islanding, the power imbalance value is 0.54 MW. The proposed $UFLS_{AHP}$ shows that 0.3730 MW of load is shed from the system. This shows that the proposed $UFLS_{AHP}$ is able to provide the optimum load shed value. The $UFLS_{AHP}$ shows the improvement of voltage magnitude profile. Also, the frequency response is successfully recovers to its nominal value without overshoot in its response.

This is due to fact that for $UFLS_{AHP}$, the BR_{AHP} is developed by considering the least error between the load generation and total load demand in the system. Also, the BR_{AHP} is developed for $UFLS_{AHP}$, which is regarded combination of the stability criteria and load criteria in the system using AHP decision making.

Table 6.7: Analysis for bus number and load shed amount for Case I

Bus number	1012	1013	1047	1079	1046	1018	1019	1020	1056	1058	1057	1154	1050	1029	1064	1151	1141	1004	1010	1039	**Total shed amount (MW)**
Load category	Non-vital	Non-vital	Non-vital	Non-vital	Semi-vital	Semi-vital	Vital	Semi-vital	Vital	Non-vital	Non-vital	Semi-vital	Non-vital	Semi-vital	Semi-vital	Vital	Non-vital	Semi-vital	Non-vital	Non-vital	
Techniques																					
UFLS$_{AHP}$	√										√									√	0.3730
UFLS$_{VS_LC}$	√										√						√		√	√	0.5826
UFLS$_{ADAP}$	√	√	√	√									√				√			√	0.6209
UFLS$_{CONV}$	√	√	√	√									√				√		√	√	0.7509

6.6.2 Case II – Load increment at 60.0s

The performance of the proposed UFLS_{AHP} is analysed during sudden load increment in the system. Thus, in order to test the effectiveness of the proposed scheme, the voltage magnitude profile for UFLS_{AHP} is compared with the $\text{UFLS}_{\text{VS\_LC}}$ (for VSI), $\text{UFLS}_{\text{ADAP}}$, and $\text{UFLS}_{\text{CONV}}$, as shown in Figure 6.10. It can be summarized that voltage magnitude for the proposed UFLS_{AHP} (indicated by the red line) is much higher than the other load shedding scheme. Out of 20 buses, 19 buses show higher voltage magnitude, which is contributed 95% of the improvement.

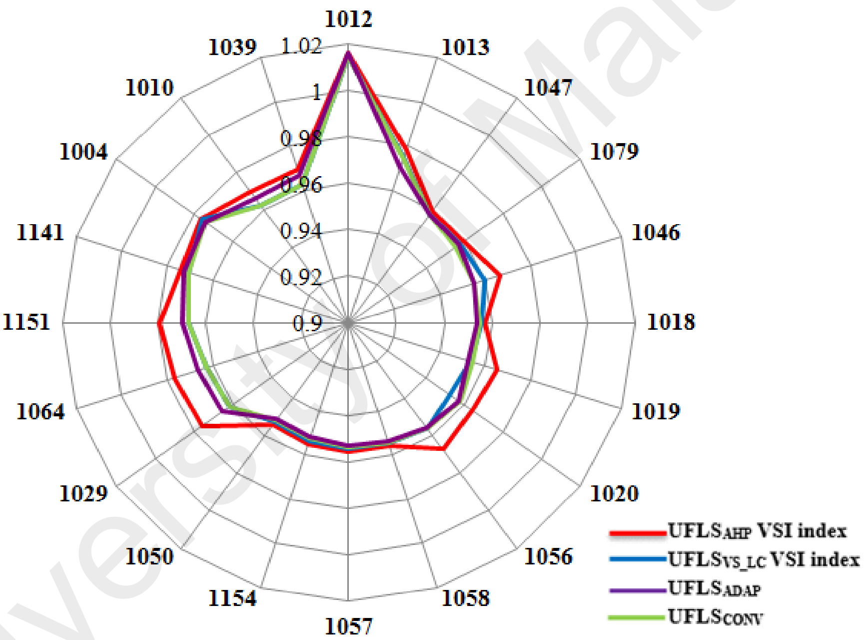


Figure 6.10: Comparison of voltage magnitude profile for Case II

Figure 6.11 shows the frequency response for multiple load shedding techniques. It can be observed that there is no overshot in the frequency performance for the proposed UFLS_{AHP}. In the case of the $\text{UFLS}_{\text{ADAP}}$ and $\text{UFLS}_{\text{CONV}}$, although the system not contains an overshoot, the frequency response requires too much time to recover to its nominal value compared to the proposed of UFLS_{AHP}. Although the $\text{UFS}_{\text{VS\_LC}}$ system can recover quickly, however, its frequency response contains some overshoot.

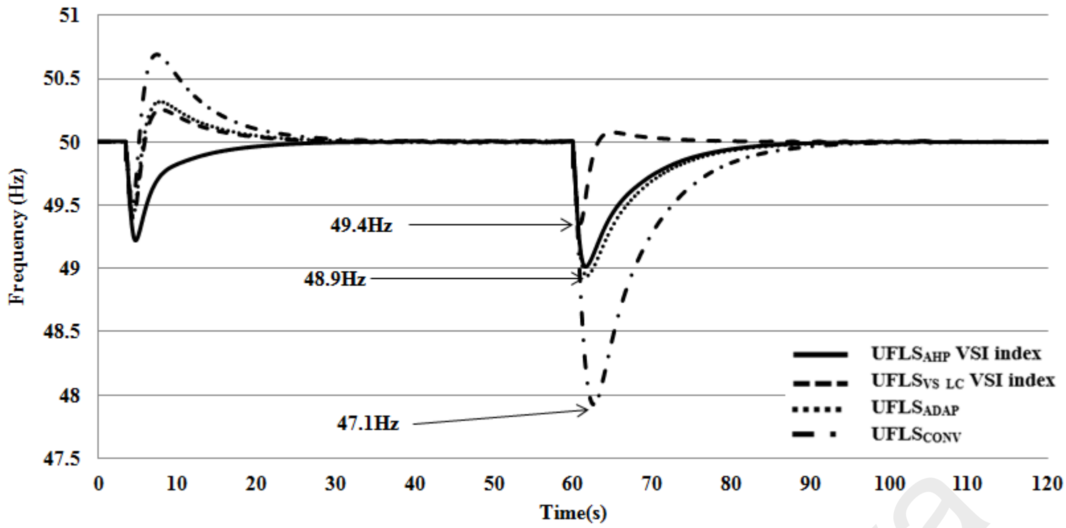


Figure 6.11: Comparison of frequency responses for Case II

Table 6.8 shows the total shed amount for the proposed $UFLS_{AHP}$, $UFLS_{VS\_LC}$, $UFLS_{ADAP}$ and $UFLS_{CONV}$. It can be concluded that proposed $UFLS_{AHP}$ shows lesser load shed, at 0.2776 MW, compared to the other load shedding scheme. It can be summarized that the proposed of $UFLS_{AHP}$ is able to provide the best load selection for load shedding, which is considered stable and least prone to error in the BR_{AHP}. Also, the $UFLS_{AHP}$ shows no overshoot of its frequency response. It can therefore be concluded that proposed $UFLS_{AHP}$ successfully provides the best load selectivity based on the developed BR_{AHP} from the proposed AHPM.

Table 6.8: Analysis for bus number and load shed amount for Case II

Bus number	1012	1013	1047	1079	1046	1018	1019	1020	1056	1058	1057	1154	1050	1029	1064	1151	1141	1004	1010	1039	**Total shed amount (MW)**
Load category	Non-vital	Non-vital	Non-vital	Non-vital	Semi-vital	Semi-vital	Vital	Semi-vital	Vital	Non-vital	Non-vital	Semi-vital	Non-vital	Semi-vital	Semi-vital	Vital	Non-vital	Semi-vital	Non-vital	Non-vital	
Techniques																					
UFLS$_{AHP}$										√							√				0.2776
UFLS$_{VS_LC}$			√										√								0.3210
UFLS$_{ADAP}$										√	√								√		0.5170
UFLS$_{CONV}$						√	√								√	√					0.6350

6.7 Discussion

The simulation results of the proposed of $UFLS_{AHP}$ are described in this section. The effectiveness of the proposed scheme is compared with $UFLS_{VS\_LC}$, $UFLS_{ADAP}$, and $UFLS_{CONV}$. The two sets of MELC are selected from the proposed $UFLS_{VS\_LC}$. The idea is to ensure that the best load is selected, considering the wide possibility between the stability criteria and the load criteria in the system. The weight for each criteria and alternative is analysed by using AHP decision-making analysis. From the simulation results, it can be noticed that proposed of AHPM is capable of ranking all of the possible alternatives based on the weight value. It should also point out that each VS index shows different weights value for each criterion, as well as for the alternatives.

According to the simulation result from Case I, the proposed $UFLS_{AHP}$ shows higher voltage magnitude improvement, which is 90% of the load buses is improved after load shed. Also, this technique shows less amount of shed load (0.3730 MW), compared to the other techniques. Meanwhile, there is no overshoot in the frequency response and the frequency successfully recovered to its nominal value. The smooth frequency response without overshoot may be used as a factor for the justification of optimal load shedding.

Furthermore, from the simulation results of Case II, the proposed $UFLS_{AHP}$ shows that 95% of total load buses have been increased its voltage magnitude compared to $UFLS_{VS\_LC}$, $UFLS_{ADAP}$ and $UFLS_{CONV}$ schemes. Also, in term of frequency response, the proposed $UFLS_{AHP}$ shows much faster of recovery time. Furthermore, the system not contains an overshoot in the system frequency. This confirms that the proposed $UFLS_{AHP}$ successfully achieves the optimal load shedding scheme and enhances the load selectivity for the load shedding process in the system.

6.8 Chapter Summary

This chapter details the proposed $UFLS_{AHP}$ based on the AHP decision making technique for load selectivity. The weight for each bus is analysed which is considered the balance comparison between stability criteria and load criteria. In this proposed scheme, two sets of MELC are selected from the proposed OCLEM. From the MELC, the BR_{AHP} is developed according to the weight calculated for the criteria and all alternatives (bus number) in the system.

From the results, it can be pointed out that the proposed of $UFLS_{AHP}$ shows a better system performance for the voltage and frequency after the load is shed from the system. Also, the load which is selected from the BR_{AHP}, has an ability to provide an optimal combination for load selectivity in the system, which is the main contribution in proposed $UFLS_{AHP}$.

CHAPTER 7: CONCLUSION

7.1 Conclusion

The increasing demand of electricity has brought the potential of Distributed Generations (DG) based on renewable energy sources. Although DG offers many benefits, its full utilization faces some obstacles due to technical reasons. A technical issue referred as unintentional islanding is the most critical issues need to be solved. In order to ensure the successful of islanding operation, the crucial task is to control the frequency and voltage within the allowable limit so that it will not cause system blackout. To address these matters, this thesis outlined four objectives in order to develop an effective load shedding scheme for islanded distribution system considering frequency and voltage stability.

The first objective in proposing a new load shedding scheme based on combination of frequency and voltage stability has been achieved. The proposed scheme successfully shed critical voltage stability bus without compromising the frequency stability of the system. This proposed scheme is referred as $UFLS_{VS}$ and was elaborated in details in Chapter 3. The simulation results of islanding and load increment presented in Chapter 5 proven that the proposed $UFLS_{VS}$ scheme produced voltage magnitude improvement following islanding and load increment scenario. The improvement was in the range of 70% to 100% from the total number of buses in the system network during islanded or load increment events. The voltage magnitude of all busses and system frequency are within allowable limit. Furthermore, the proposed scheme also outperformance conventional and adaptive schemes in both voltage and frequency as presented in Chapter 5.

The second objective of this research highlighted the analysis of seven different VS index in the application of the proposed load shedding scheme. The applied voltage stability indices are SI, VSI, PSI, FVSI, NLSI, Lp and Lmn. The analysis on these indices found that by applying any of these indices in the proposed load shedding scheme, critical buses (close to collapse point) was managed to shed from the system. As a result, significant overall voltage magnitude improvement can be achieved as presented in Chapter 5. From the overall performance between these indices, it was found that VSI index is the most consistent in producing highest voltage improvement when applied in the proposed load shedding scheme. Only one case-light load case II (Figure 5.33), it produced overall voltage magnitude lower than Lmn and SI. Although the VSI lower than Lmn and SI, the overall voltage magnitude is within allowable limit. Based on this finding, VSI index is applied in the fourth objective of this work.

In the third objective, the optimal selectivity of load is formulated based on minimum error of power-load value. This proposed algorithm has been presented in Chapter 4. From this, the combination of buses which have the least error from the non-vital load category (difference between power generation and active power load) was selected for load shedding. This algorithm and the best voltage stability index, which is VSI are incorporated into the proposed load shedding scheme based on Analytical Hierarchy Process (AHP) method, which was the fourth objective of this work. From the simulation results presented in Chapter 6, it has been observed that proposed load shed based on AHP provide much improvement of voltage profile compared voltage stability and load category load shed, conventional and adaptive load shedding. The simulation results of islanding and load increment presented in Chapter 6 proven that the proposed load shed based on AHP scheme produced voltage magnitude improvement for both case (islanding and load increment). The improvement was in the range of 90% to 95% from the total number of buses in the system network during system islanded or load increment. Also, this finding can be validated an ability of VS index (especially VSI) used as one criteria considered for load selectivity in AHP decision making analysis. Furthermore, the proposed of load selectivity for load shedding scheme possess advantages to provide an optimal load shedding, where the frequency response successfully recovered with fast recovery time without overshoot.

7.2 Future Works

This thesis has covered two main important issues of islanding operation of the distribution system connected with rotating type DGs. The proposed scheme can also be improved in the future according to the following recommendations:

1) The proposed scheme considered only rotating type of DGs in the islanded system. It is suggested that the scheme to consider inverter-based DG such as Photovoltaic and Wind energy. This include the modelling of inverter controller, and the photovoltaic and wind energy of DG model. The voltage and current control should be considered to control the intermittent parameters for solar and wind energy.
2) The research work is considering islanded system for the load shedding. The proposed load shedding controller is possible to be combined with load restoration procedure to automatically perform the reconnection of disconnected loads.
3) The islanded distribution network is reconnected to the grid once the fault that caused the islanding has been identified and removed. This can be accomplished with automatic grid reconnection scheme in the test system. In order to perform the successful islanding operation of distribution network connected with DG, grid reconnection technique may be proposed and integrated with the proposed scheme.

4) To improve the proposed scheme, larger and complex network is proposed to be used in testing the scheme. For VS analysis, the advance of communication links should be implemented in order to retrieve the parameters from system. Also, several islanded areas should be created and another criterion should be considered in AHP analysis for load selectivity.
5) Other decision-making techniques such as Topsis-AHP, Fuzzy-AHP, Fuzzy-Topsis can be explored in determining load shedding selectivity.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

Following papers have been published and submitted in journals and conferences from this research studies.

A. Journal Publications

1) **N.M.Sapari**, H. Mokhlis, A.H.A. Bakar, H.Mohamad, Javed Ahmed Laghari, M.R.M.Dahalan**,** "Load Shedding Scheme based on Rate of Change of Frequency and Ranked Stability Index for Islanding Distribution System Connected to Mini Hydro", IEEJ Transactions on Electrical and Electronics Engineering - ISI Cited Publication, Published

2) **N.M.Sapari**, H. Mokhlis, Javed Ahmed Laghari , A.H.A. Bakar, H.Mohamad, M.R.M.Dahalan**,** "Load Shedding Scheme based on Frequency and Voltage Stability for Islanding Operation of Distribution Network Connected to Mini-Hydro Generation, Turkish Journal of Electical Engineering & Computer Science – ISI Cited Publication, Published

3) **N. M. Sapari**, H. Mokhlis, Javed Ahmed Laghari, A.H.A. Bakar, M.R.M. Dahalan, "Application of Load Shedding Schemes for Distribution Network Connected with Distributed Generation: A review", The Renewable & Sustainable Energy Reviews – ISI Cited Publication, Published

4) N. A. Yusuf, H.M.Rosli, H.Mokhlis, M.Karimi, J.Selvaraj, **N.M.Sapari**, "A New Under Voltage Load Shedding Scheme for Islanded Distribution System Based on Voltage Stability Indices", IEEJ Transactions on Electrical and Electronics Engineering - ISI Cited Publication, Published

B. Conference Publications

1) **N.M. Sapari**, H. Mokhlis, A.H.A. Bakar, M.R.M. Dahalan, “Online Stability Index Monitoring for Load Shedding Scheme in Islanded Distribution Network”, IEEE 8th International Power Engineering and Optimization Conference (PEOCO2014), (ISI-Cited Publication) - Oral Presentation

2) H.Mohamad, **N.M. Sapari**, S.Dahlan, N.N.Y.Dahlan, “Under-Frequency Load Shedding Technique Considering Response Based For Islanding Distribution Network Connected With Mini Hydro”, IEEE 8th International Power Engineering and Optimization Conference (PEOCO2014), (ISI-Cited Publication) - Oral Presentation

3) N. A. Yusof, H. Mokhlis, M. Karimi, J. A. Laghari, H. A. Illias, **N. M. Sapari**, "Under-Voltage Load Shedding Scheme Based on Voltage Stability Index for Distribution Network", 3rd IET International Conference on Clean Energy and Technology 2014 (CEAT), (ISI-Cited Publication)

4) M.R.M. Dahalan, **N. M. Sapari,** H.Mokhlis, Z. Zainol**,** “Combination of Event and Response Based Strategy Applied For Adaptive Under Frequency Load Shedding Algorithms for Islanded Distribution System”, Engineering Technology & Marine Applications Conference 2011